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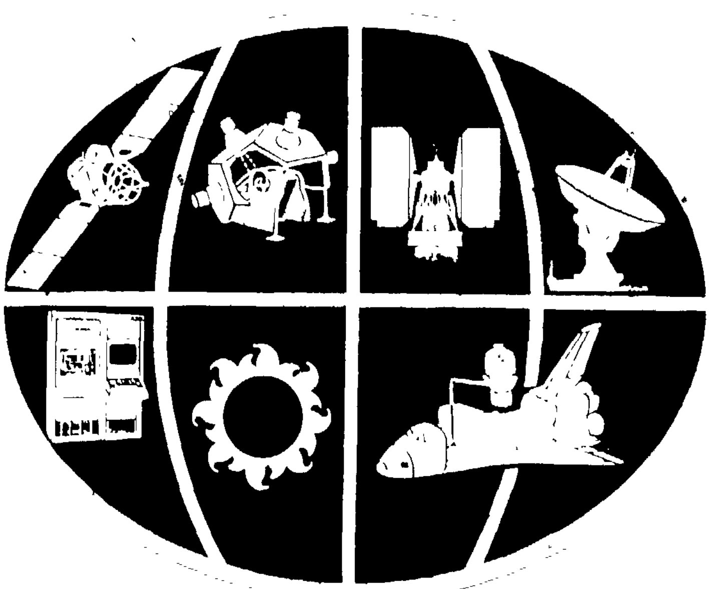
VIBROACOUSTIC TEST PLAN EVALUATION

PARAMETER VARIATION STUDY

Prepared Under: Contract NAS 5-20906

Prepared for
THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Goddard Space Flight Center



space division

GENERAL ELECTRIC

FOREWORD

The study presented herein was performed by the General Electric Space Division, Valley Forge, Pennsylvania, for the NASA Goddard Space Flight Center under contract NAS 5-20906. The study was performed in three phases:

1. Phase A - Study on Component Environmental Specification Development and Test Techniques.
2. Phase B - Study on Development of Cost Effective Alternate Approaches to Creating Shuttle Spacelab Payload Environmental Test Requirements.
3. Phase C - Continued Study on Development of Cost Effective Alternate Approaches to Creating Shuttle Spacelab Payload Environmental Test Requirements.

The principal investigator was Harold R. Gongloff and the Program Manager was Clyde V. Stahle. The NASA technical monitors were W. Brian Keegan and Joseph P. Young, who provided valuable guidance throughout the course of this study.

The results of Phases A and B were presented in the three-volume report, "Vibroacoustic Test Plan Evaluation", GE Document No. 76SDS4223, June 1, 1976. The results of Phase C are presented in this report.

SUMMARY

This report presents the results obtained from the Phase C portion of this study to optimize Shuttle Spacelab payload vibroacoustic test requirements such that design defects can be corrected in a cost effective manner. In this portion of the study the statistical decision models developed during the Phase B portion of the study were modified and used to evaluate the cost effectiveness of seven new alternate vibroacoustic test plans and to determine the optimum test levels associated with each plan. The test plans included no testing, component testing, subassembly testing, or payload testing and combinations of component and subassembly testing or component and payload testing. Protoflight components were considered at all levels of testing since it was shown during the Phase B portion of the study that the use of prototype components was not cost effective. Two structural test options, either no structural test or protoflight structural test, were considered for the new test plans because during the Phase B portion of the study the use of a prototype Structural Development Model increased the expected costs.

The methodology developed during Phase B was modified for the Phase C study. A decision model is used to evaluate the expected cost of a shuttle payload program using the alternate vibroacoustic test plans. The environment during ground testing and flight is represented as a log normal distributed random variable, including spatial variations evaluated during the Phase A portion of the study and flight to flight excitation variations estimated during the Phase B portion from launch vehicle acoustic measurements. The vibroacoustic strength of payload components is also treated as a log normal distributed random variable using the results of previous studies. Using a

stress-strength type of statistical analysis, the probabilities of component failures during ground testing and flight are estimated, considering the vibroacoustic test program to significantly change the component strength distribution. The effect of the vibroacoustic test environments on the component strength accounts for cumulative damage and incipient failures. These probabilities are then used to establish the probability of achieving a completely successful or partially successful flight using a reliability model of the payload at the component level of assembly. By combining the probabilities of flight and vibroacoustic test failures with their estimated costs the expected program cost is estimated. The decision model treats the vibroacoustic test levels as parameters to facilitate the determination of the best vibroacoustic test plan and the associated test levels.

Except for the modifications described in this report, the simplications and assumptions made to develop the methodology during Phase B apply also to the Phase C study. A flight by flight evaluation of the flight failure probability was made during Phase C to obtain a more accurate representation. From this evaluation a single mission reliability equivalent to the average reliability over NF missions was obtained. The cost of designing components for increasing vibration levels was formulated as a function of the vibration test level and was included in the Phase C study.

Sensitivity analyses were performed to evaluate the effect of some potentially critical parameters on the optimum expected program costs and the associated vibroacoustic test levels. The parameters that were made variable were:

1. The shuttle payload bay internal acoustic environment
2. The STS launch cost per flight

3. The degree of redundancy in the components of the housekeeping section of the payload reliability model.

4. The retest/repair cost of components that fail during ground testing and flight.

A total of 196 cases were studied during Phase C, seven conditions (a revised baseline and six variations) for seven test plans and four payload configurations.

The optimum vibroacoustic test levels that provided the minimum expected project cost were determined and the vibroacoustic test plans were ranked according to cost and reliability. Except for the less complex payload configurations, the test plan cost rank for the revised baseline, starting with the plan that yielded the lowest minimum cost, was:

1. Subassembly testing only
2. System testing only
3. Component and subassembly testing
4. Component and system testing
5. No testing
6. Component and protoflight structure testing
7. Component testing only

For the less complex payload configurations rankings 5 and 6 were reversed. Large variations occurred in the optimum expected project cost obtained for the parameter variations of the vibroacoustic test plans; the largest variation was $5.3 million. The lowest cost approach eliminated component testing and maintained a high flight vibroacoustic reliability by performing subassembly tests at a relatively high acoustic level. To realize the indicated cost saving, new contractual relations are needed to obtain the required support from the component suppliers.

For the parameter variations considered in this study the vibroacoustic test plan cost and reliability rankings, the optimum expected project costs, and the associated test levels vary with the test plan, payload, and parameter being varied. The most sensitive parameters were the shuttle payload bay internal acoustic environment and the STS launch cost. The optimum expected project costs and the associated test levels increase as the shuttle payload bay internal acoustic environment and the STS launch cost increase for all test plans and payload configurations. The optimum expected project costs and the associated component vibration test/design level increase as the component retest/repair cost for failures that occur during assembly level testing and flight increases, but the associated assembly acoustic test level varies with the test plan and payload. As the degree of redundancy in the housekeeping section of the payload increases the optimum expected project cost increases, but the associated test levels decrease.

The methodology is now developed to the point that optimum expected project costs and the associated test levels can be achieved for each alternate vibroacoustic test plan considered. It is recommended that more sensitivity analyses be performed to evaluate the effects of other parameters. To facilitate such analyses, the computer codes that were written during Phase B and Phase C should be reviewed, coordinated, optimized, and documented so that more people can utilize them to examine methods of reducing program costs for specific payload configurations.

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SECTION 1

INTRODUCTION

The objective of this Phase C portion of the study is to continue the development of cost effective alternate approaches to creating Shuttle Spacelab payload vibroacoustic test requirements. Previous studies have indicated that statistical decision models provide a viable method of evaluating the cost effectiveness of alternate vibroacoustic test plans and the associated test levels. The methodology developed in this study provides a major step toward the development of a realistic tool to quantitatively tailor test programs to specific payloads. Testing is considered at the no test, component, subassembly, or system level of assembly. Component redundancy and partial loss of flight data are considered. Most direct and probabilistic costs are considered and incipient failures resulting from ground tests are treated. Optimums defining both component and assembly test levels are indicated for the modified test plans considered in this portion of the study. Modeling simplifications must be considered in interpreting the results relative to a particular payload. New parameters introduced to this portion of the study were a no test option, flight by flight failure probabilities, and a cost to design components for higher vibration requirements. Parameters varied for this study were the shuttle payload bay internal acoustic environment, the STS launch cost, the component retest/repair cost, and the amount of redundancy in the housekeeping section of the payload reliability model.

The Phase C portion of the study was expanded beyond the consideration of a typical payload subjected to a prescribed shuttle environment. The shuttle payload bay internal acoustic environment (145 dB OA) of the STS Payload Accommodations document, Reference 1, was applied as the baseline environment. The sensitivity of the results to this parameter was examined by considering alternate acoustic environments of 135 dB OA and 150 dB OA. Cost variability and redundancy variations were also examined.

To perform these parameter studies, the mathematical models developed for Phase B, Reference 2, were modified. The statistical estimates of flight failure probabilities were improved by developing a method to calculate flight by flight failure probabilities in order to obtain a single mission reliability equivalent to the average reliability over NF missions. The cost effectiveness of a no-test option was evaluated by adding a new test plan. Other test plans were modified so that protoflight components were used at all levels of assembly. Another new item was the cost associated with designing hardware to vibration levels in excess of those normally used with conventional spacecraft.

Statistical decision theory was applied to the evaluation of seven vibroacoustic test plans. All test plans evaluated during both Phase B and Phase C are given in Table 1-1. Test Plans 1 through 5 were evaluated during Phase B. Test Plans 4 through 9 were considered in this Phase C study.

The following sections of this report present the results of the Phase C study. The modifications made to the mathematical models of Phase B are presented in Section 2. The considerations made for the parameter variations are discussed in Section 3. The Phase C results are presented in the test plan evaluation given in Section 4. The conclusions and recommendations are presented in Section 5.

Table 1-1

Vibroacoustic Test Plan Matrix

Test Plan No.	Component Test	Subassembly Test	System Test	Structure Test
1	Mix*	-	-	-
1A	Mix	-	-	SDM**
2	Mix	Protoflight	-	Protoflight
3	Mix	-	Protoflight	Protoflight
3A	Mix	-	Protoflight	SDM
4	-	Protoflight	-	Protoflight
5	-	-	Protoflight	Protoflight
6	-	-	-	-
7	Protoflight	-	-	-
7B	Protoflight	-	-	Protoflight
8	Protoflight	Protoflight	-	Protoflight
9	Protoflight	-	Protoflight	Protoflight

* Prototype housekeeping components and protoflight experiment components

** Prototype Structural Development Model

NOTE: Test Plans 1 - 5 were considered in the Phase B study.
Test Plans 4 - 9 were considered in the Phase C study.

SECTION 2
MODEL REVISIONS

The objective of the Phase C study was to generalize the investigation performed in the Phase B study, Reference 2, to include the effects of the acoustic environment and of critical parameter variations on alternate vibroacoustic test plans and the associated test requirements. To accomplish this a modified set of test plans was used, investigations of design costs and flight by flight failure probabilities were performed, and key parameters were varied. The modified test plans are discussed in Section 1. The variation of key parameters is discussed in Section 3. The design cost and flight by flight failure probabilities are discussed in this section. The decision models developed in Phase B were modified to include these revisions.

2.1 DESIGN COST

The cost of designing components to higher vibration levels is difficult to estimate. Early discussions with packaging engineering led to the conclusions that the design work normally done for existing components would be performed using different load factors and may cause some minor changes in packaging methods, but did not appear to be appreciable. The primary increases in costs were felt to be encountered during the test phase when failures which require modifications of the equipment occur. This redesign/retest cost was not included in the Phase B study, but was added to the Phase C study.

The design cost as a function of the component vibration test/design level was investigated further from the program manager and component vendor points of view. As the component vibration requirement is increased, there is obviously an increased risk of problems arising during the test phase if methods of increasing the dynamic design adequacy of the package are not incorporated. This implies that a program manager responsible for component development would either allow additional design time or additional test time to account for anticipated vibration problems. A quantification of the component design cost as a function of the component vibration level was developed after discussions with program managers and component vendors.

To obtain this quantification the following considerations were made:

1. For a component vibration requirement of 10 g rms, there is no design cost.
2. For a component vibration requirement of 40 g rms, there is a design cost of $10,000 per component.
3. For an extreme component vibration requirement of 100 g rms, the design cost becomes extremely high.

Fitting an equilateral hyperbola to these three points yields the equation expressing the expected cost (in thousands of dollars) of designing components to higher vibration levels, $E\{C_{DES}\}$, as a function of the component vibration test/design requirement, g.

$$E\{C_{DES}\} = \frac{1800}{100 - g} - 20. \qquad 10 \leq g \leq 100 \qquad (2\text{-}1)$$

For this study an upper bound of $160,000 was established for component vibration requirements above 90 g rms.

Equation (2-1) gives the cost, in thousands of dollars, for a single component. This design cost was included as an additional direct cost to the cost models of all the test plans. The effects of the design cost are evident on the optimum cost graphs, Figures 4-1 to 4-28. The pronounced increase in the expected cost at the higher g levels is a direct result of the design cost, particularly for those test plans (Test Plans 4, 5, 6) which have no testing at the component level of assembly. The most significant effect of the design cost is that, for Phase C, optimum costs and the associated test levels are obtained for all test plans. This was not achievable for Test Plans 4 and 5 of the Phase B study.

2.2 FLIGHT BY FLIGHT FAILURE PROBABILITIES

The purpose of this consideration was to obtain a single mission reliability equivalent to the average reliability over NF missions. For Phase B the flight failure probabilities were determined by using vibration reliabilities for the components that were based on an average exposure duration over the total number of flights ($t_F = \frac{15 \text{ missions} * 8 \text{ sec/mission}}{2} = 60$ sec.). In this Phase C study an investigation was made to determine if a flight by flight estimate could be used to improve the representation. Using the transformation of the component strength to account for cumulative damage, the strength can be determined as a function of the cumulative flight exposure duration. Each of the transformed strength curves can then be used in a stress-strength analysis to determine the probability of a failure for a selected value of the cumulative flight exposure.

The method of transforming the strength distribution was presented in Section 3 of Reference 2. For Phase C the following expression is employed to calculate the flight by flight data.

$$P_{ST}^3 = P_Q^3 + \frac{t_F}{t_S} \left[P^3 + (I-1) P_M^3 \right] \qquad (2\text{-}2)$$

where

P_{ST} = transformed assembly test pressure

P_Q = pressure associated with the assembly acoustic test level

P = variable pressure

P_M = mean pressure

t_F = individual mission flight time
= 8 seconds per flight

t_S = assembly test time
= 120 seconds

I = number of flights
= 1,2, ... , 15

The vibration reliabilities obtained by applying Equation (2-2) represent the individual flight failure probabilities. The mean pressure is used to account for the expected damage from the previous flights. Vibration reliability data for 2 component vibration test levels, 8 assembly test levels, and 3 shuttle acoustic environments were obtained for Test Plan 9. The average vibration reliability was determined for 15 missions. In all cases this average value occurred between 7 and 8 missions. These data are presented in Tables 2-1, 2-2, and 2-3 for the 145, 135, and 150 dB environments, respectively. In these tables the accummulated flight time, AFT, is given for each of the 15 missions.

The data for the 145 dB environment were then evaluated to obtain the average vibration reliability after 1, 2, ..., 15 missions and obtained the single mission that would satisfy the average for each case. From this analysis a pattern evolved and was generalized for the 1 to 15 mission data to yield the following relationship between the number of missions planned for the given payload (NF) and the equivalent single flight number for which the vibration reliability data are calculated.

Flight number = [Integer part of (NF/2)] + 1 (2-3)

Equation (2-3) was applied to obtain the equivalent single flight number (8) that was used to evaluate the 15 missions (NF) Shuttle Spacelab payload considered in the

Table 2-1

Protoflight Flight by Flight Vibration Reliability Summary
Test Plan 9, 145 dB Environment

PROTOFLIGHT FLIGHT-BY-FLIGHT VIBRATION RELIABILITY SUMMARY FOR 15 FLIGHTS, 2 UV'S, AND 8 SPL'S, FLRVS

AFT	UV	SPL (DB) / G (RMS)	143.0	145.0	147.0	149.0	151.0	153.0	155.0	157.0
8.0	1.2	8.035	0.99814676	0.99832193	0.99926836	0.99955436	0.99973290	0.99984217	0.99990776	0.99994656
8.0	2.6	48.333	0.99968122	0.99976968	0.99983777	0.99988839	0.99992492	0.99995041	0.99996773	0.99997925
16.0	1.2	8.035	0.99672248	0.99771038	0.99870026	0.99920807	0.99952354	0.99971996	0.99983669	0.99990577
16.0	2.6	48.333	0.99943834	0.99959226	0.99971258	0.99980256	0.99986744	0.99991279	0.99994360	0.99996409
24.0	1.2	8.085	0.99732680	0.99700306	0.99813543	0.99886264	0.99931851	0.99959782	0.99976570	0.99986496
24.0	2.6	48.333	0.99919957	0.99941669	0.99958803	0.99971687	0.99980992	0.99987522	0.99991951	0.99994901
32.0	1.2	8.035	0.99395615	0.99611525	0.99757345	0.99851824	0.99911175	0.99947584	0.99969465	0.99982424
32.0	2.6	48.333	0.99896547	0.99924288	0.99946415	0.99963138	0.99975261	0.99983764	0.99989538	0.99993383
40.0	1.2	8.035	0.99261542	0.99523123	0.99701437	0.99817461	0.99890519	0.99935379	0.99962376	0.99978352
40.0	2.6	48.333	0.99873537	0.99907080	0.99934096	0.99954630	0.99969530	0.99980002	0.99987119	0.99991360
48.0	1.2	8.035	0.99120774	0.99435622	0.99643820	0.99783201	0.99869890	0.99923202	0.99955285	0.99974278
48.0	2.6	48.333	0.99851050	0.99890034	0.99921852	0.99946128	0.99963808	0.99976252	0.99984719	0.99990357
56.0	1.2	8.035	0.99000305	0.99346975	0.99591497	0.99749035	0.99849300	0.99911024	0.99948205	0.99970193
56.0	2.6	48.333	0.99823906	0.99873181	0.99909664	0.99937637	0.99958097	0.99972495	0.99982305	0.99988832
64.0	1.2	8.085	0.98873112	0.99263162	0.99535462	0.99714952	0.99828736	0.99899839	0.99941118	0.99966119
64.0	2.6	48.333	0.99807151	0.99856482	0.99897523	0.99929172	0.99952395	0.99968733	0.99979906	0.99987319
72.0	1.2	8.035	0.98745070	0.99178186	0.99480695	0.99680949	0.99808193	0.99886695	0.99934028	0.99962355
72.0	2.6	48.333	0.99783777	0.99839947	0.99885464	0.99920764	0.99946694	0.99964992	0.99977505	0.99985798
80.0	1.2	8.085	0.98625125	0.99094001	0.99426208	0.99647052	0.99787691	0.99874536	0.99926938	0.99957978
80.0	2.6	48.333	0.99764732	0.99823552	0.99873448	0.99912346	0.99941009	0.99961241	0.99975087	0.99984288
88.0	1.2	8.035	0.98504156	0.99010602	0.99372003	0.99613253	0.99767202	0.99862398	0.99919869	0.99953908
88.0	2.6	48.333	0.99744056	0.99807322	0.99861507	0.99903964	0.99935321	0.99957505	0.99972683	0.99982778
96.0	1.2	8.085	0.98385111	0.98927955	0.99318053	0.99579522	0.99746753	0.99850250	0.99912783	0.99949830
96.0	2.6	48.333	0.99723699	0.99791240	0.99847624	0.99895599	0.99929649	0.99953765	0.99970282	0.99981272
104.0	1.2	8.035	0.98267875	0.98846051	0.99264384	0.99545885	0.99726327	0.99838120	0.99905703	0.99945763
104.0	2.6	48.333	0.99703650	0.99775304	0.99837709	0.99887260	0.99923980	0.99950024	0.99967874	0.99979754
112.0	1.2	8.035	0.98152410	0.98764380	0.99210973	0.99512345	0.99705916	0.99825991	0.99898630	0.99941708
112.0	2.6	48.333	0.99683893	0.99759508	0.99826027	0.99878936	0.99918321	0.99946288	0.99965474	0.99978232
120.0	1.2	8.035	0.98038630	0.98684433	0.99157825	0.99478878	0.99685544	0.99813888	0.99891550	0.99937632
120.0	2.6	48.333	0.99664442	0.99743851	0.99814309	0.99870624	0.99912664	0.99942557	0.99963080	0.99976723

AVERAGE PROTOFLIGHT FLIGHT-BY-FLIGHT VIBRATION RELIABILITY SUMMARY FOR 15 FLIGHTS, 2 UV'S, AND 8 SPL'S, FLRV

UV	SPL (DB) / G (RMS)	143.0	145.0	147.0	149.0	151.0	153.0	155.0	157.0
1.2	8.035	0.98893437	0.99270836	0.99538074	0.99715792	0.99828997	0.99898925	0.99941132	0.99966132
2.6	48.333	0.99810632	0.99857978	0.99898104	0.99929400	0.99952464	0.99968764	0.99979910	0.99987321

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Table 2-2

Protoflight Flight by Flight Vibration Reliability Summary
Test Plan 9, 135 dB Environment

PROTOFLIGHT FLIGHT-BY-FLIGHT VIBRATION RELIABILITY SUMMARY FOR 15 FLIGHTS, 2 UV'S, AND 8 SPL'S, FLRVS

AFT	UV	SPL (DB) / G (RMS)	133.0	135.0	137.0	139.0	141.0	143.0	145.0	147.0
8.0	1.2	2.557	0.99857612	0.99907485	0.99941332	0.99963543	0.99977740	0.99986581	0.99991993	0.99995262
8.0	2.6	15.284	0.99979720	0.99984889	0.99989025	0.99992216	0.99994586	0.99996294	0.99997495	0.99998301
16.0	1.2	2.557	0.99748273	0.99835980	0.99895883	0.99935311	0.99960540	0.99976294	0.99985925	0.99991729
16.0	2.6	15.284	0.99964296	0.99973358	0.99980677	0.99986336	0.99990547	0.99993578	0.99995715	0.99997163
24.0	1.2	2.557	0.99641176	0.99765217	0.99850673	0.99907155	0.99943365	0.99966003	0.99979861	0.99988198
24.0	2.6	15.284	0.99949195	0.99961932	0.99972366	0.99980459	0.99986513	0.99990869	0.99993932	0.99996011
32.0	1.2	2.557	0.99536065	0.99695182	0.99805694	0.99879065	0.99926210	0.99955720	0.99973794	0.99984558
32.0	2.6	15.284	0.99934375	0.99950635	0.99964098	0.99974606	0.99982471	0.99988161	0.99992149	0.99994883
40.0	1.2	2.557	0.99432990	0.99625864	0.99760957	0.99851072	0.99909086	0.99945443	0.99967726	0.99981136
40.0	2.6	15.284	0.99919829	0.99939440	0.99955878	0.99968766	0.99978447	0.99985447	0.99990369	0.99993738
48.0	1.2	2.557	0.99331822	0.99557223	0.99716456	0.99823129	0.99891980	0.99935175	0.99961669	0.99977519
48.0	2.6	15.284	0.99905553	0.99928369	0.99947697	0.99962940	0.99974419	0.99982753	0.99988591	0.99992591
56.0	1.2	2.557	0.99232449	0.99489254	0.99672184	0.99795278	0.99874903	0.99924906	0.99955609	0.99974077
56.0	2.6	15.284	0.99891536	0.99917419	0.99939553	0.99957140	0.99970401	0.99980046	0.99986814	0.99991435
64.0	1.2	2.557	0.99134816	0.99421962	0.99628134	0.99767490	0.99857838	0.99914664	0.99949547	0.99970560
64.0	2.6	15.284	0.99877768	0.99906560	0.99931457	0.99951343	0.99966389	0.99977336	0.99985039	0.99990301
72.0	1.2	2.557	0.99038841	0.99355299	0.99584312	0.99739776	0.99840810	0.99904412	0.99943500	0.99967024
72.0	2.6	15.284	0.99864235	0.99895814	0.99923404	0.99945562	0.99962383	0.99974636	0.99983262	0.99989157
80.0	1.2	2.557	0.98944455	0.99289265	0.99540712	0.99712136	0.99823784	0.99894177	0.99937437	0.99963499
80.0	2.6	15.284	0.99850918	0.99885144	0.99915384	0.99939810	0.99958394	0.99971942	0.99981485	0.99988014
88.0	1.2	2.557	0.98851536	0.99223852	0.99497342	0.99684570	0.99806809	0.99883934	0.99931389	0.99959979
88.0	2.6	15.284	0.99837824	0.99874592	0.99907407	0.99934060	0.99954398	0.99969245	0.99979709	0.99986378
96.0	1.2	2.557	0.98760183	0.99159038	0.99454176	0.99657076	0.99789835	0.99873716	0.99925335	0.99956459
96.0	2.6	15.284	0.99824929	0.99864135	0.99899468	0.99928332	0.99950408	0.99966556	0.99977930	0.99985728
104.0	1.2	2.557	0.98670201	0.99094804	0.99411219	0.99629651	0.99772884	0.99863491	0.99919290	0.99952928
104.0	2.6	15.284	0.99812240	0.99853772	0.99891577	0.99922599	0.99946426	0.99963855	0.99976165	0.99984581
112.0	1.2	2.557	0.98581569	0.99031139	0.99368478	0.99602305	0.99755979	0.99853282	0.99913249	0.99949401
112.0	2.6	15.284	0.99799731	0.99843511	0.99883720	0.99916911	0.99942451	0.99961160	0.99974392	0.99983445
120.0	1.2	2.557	0.98494240	0.98968043	0.99325952	0.99575025	0.99739079	0.99843061	0.99907210	0.99945335
120.0	2.6	15.284	0.99787418	0.99833317	0.99875905	0.99911214	0.99938465	0.99958469	0.99972606	0.99982304

AVERAGE PROTOFLIGHT FLIGHT-BY-FLIGHT VIBRATION RELIABILITY SUMMARY FOR 15 FLIGHTS, 2 UV'S, AND 8 SPL'S, AFLRV

UV	SPL (DB) / G (RMS)	133.0	135.0	137.0	139.0	141.0	143.0	145.0	147.0
1.2	2.557	0.99150415	0.99427974	0.99630233	0.99763172	0.99858056	0.99914725	0.99949571	0.99970563
2.6	15.284	0.99879971	0.99907526	0.99931841	0.99951485	0.99966447	0.99977355	0.99985044	0.99990304

Table 2-3

Protoflight Flight by Flight Vibration Reliability Summary
Test Plan 9, 150 dB Environment

PROTOFLIGHT FLIGHT-BY-FLIGHT VIBRATION RELIABILITY SUMMARY FOR 15 FLIGHTS, 2 UV'S, AND 8 SPL'S, FLRVS

AFT	UV	SPL (DB) / G (RMS)	148.0	150.0	152.0	154.0	156.0	158.0	160.0	162.0
8.0	1.2	14.377	0.99787527	0.99866455	0.99917952	0.99950544	0.99970661	0.99982855	0.99990108	0.99994361
8.0	2.6	85.949	0.99960907	0.99972071	0.99980613	0.99986876	0.99991320	0.99994383	0.99996431	0.99997779
16.0	1.2	14.377	0.99624103	0.99762987	0.99854135	0.99911988	0.99947790	0.99969480	0.99982339	0.99989958
16.0	2.6	85.949	0.99930840	0.99950448	0.99965553	0.99976663	0.99984561	0.99990010	0.99993658	0.99996055
24.0	1.2	14.377	0.99463951	0.99660592	0.99790671	0.99873561	0.99924944	0.99956115	0.99974676	0.99985550
24.0	2.6	85.949	0.99901388	0.99929052	0.99950560	0.99966476	0.99977804	0.99985638	0.99990890	0.99994329
32.0	1.2	14.377	0.99306935	0.99559255	0.99727531	0.99835223	0.99902129	0.99942755	0.99966965	0.99981159
32.0	2.6	85.949	0.99872508	0.99907868	0.99935665	0.99956318	0.99971068	0.99981271	0.99988116	0.99992506
40.0	1.2	14.377	0.99152894	0.99458950	0.99664730	0.99796988	0.99879347	0.99929414	0.99959256	0.99976751
40.0	2.6	85.949	0.99844168	0.99886895	0.99920821	0.99946178	0.99964334	0.99976893	0.99985345	0.99990878
48.0	1.2	14.377	0.99001672	0.99359633	0.99602248	0.99758869	0.99856605	0.99916072	0.99951550	0.99972357
48.0	2.6	85.949	0.99816359	0.99866146	0.99906081	0.99936070	0.99957615	0.99972535	0.99982575	0.99989157
56.0	1.2	14.377	0.98853164	0.99261309	0.99540101	0.99720835	0.99833873	0.99902737	0.99943848	0.99967962
56.0	2.6	85.949	0.99789045	0.99845587	0.99891390	0.99925992	0.99950895	0.99968181	0.99979810	0.99987436
64.0	1.2	14.377	0.98707235	0.99163925	0.99478269	0.99682903	0.99811196	0.99889419	0.99936138	0.99963564
64.0	2.6	85.949	0.99762206	0.99825241	0.99876792	0.99915932	0.99944190	0.99963810	0.99977041	0.99985716
72.0	1.2	14.377	0.98563790	0.99067470	0.99416739	0.99645084	0.99788527	0.99876112	0.99928440	0.99959173
72.0	2.6	85.949	0.99735810	0.99805082	0.99862266	0.99905908	0.99937501	0.99959469	0.99974263	0.99983987
80.0	1.2	14.377	0.98422731	0.98971936	0.99355543	0.99607360	0.99765896	0.99862809	0.99920737	0.99954730
80.0	2.6	85.949	0.99709868	0.99785109	0.99847810	0.99895911	0.99930800	0.99955109	0.99971513	0.99982265
88.0	1.2	14.377	0.98283938	0.98877271	0.99294644	0.99569735	0.99743310	0.99849512	0.99913049	0.99950378
88.0	2.6	85.949	0.99684339	0.99765327	0.99833429	0.99885925	0.99924129	0.99950763	0.99968741	0.99980544
96.0	1.2	14.377	0.98147335	0.98783490	0.99234041	0.99532206	0.99720732	0.99836226	0.99905356	0.99945984
96.0	2.6	85.949	0.99659211	0.99745722	0.99819119	0.99875991	0.99917455	0.99946417	0.99965980	0.99978813
104.0	1.2	14.377	0.98012844	0.98690539	0.99173753	0.99494773	0.99698192	0.99822958	0.99897669	0.99941603
104.0	2.6	85.949	0.99634469	0.99726296	0.99804884	0.99866055	0.99910798	0.99942077	0.99963211	0.99977095
112.0	1.2	14.377	0.97880381	0.98598424	0.99113749	0.99457447	0.99675683	0.99809676	0.99889977	0.99937204
112.0	2.6	85.949	0.99610095	0.99707055	0.99790708	0.99856163	0.99904135	0.99937738	0.99960444	0.99975383
120.0	1.2	14.377	0.97749862	0.98507119	0.99054049	0.99420204	0.99653205	0.99796427	0.99882307	0.99932820
120.0	2.6	85.949	0.99586087	0.99687971	0.99776616	0.99846293	0.99897491	0.99933400	0.99957687	0.99973569

AVERAGE PROTOFLIGHT FLIGHT-BY-FLIGHT VIBRATION RELIABILITY SUMMARY FOR 15 FLIGHTS, 2 UV'S, AND 8 SPL'S, AFLRV

UV	SPL (DB) / G (RMS)	148.0	150.0	152.0	154.0	156.0	158.0	160.0	162.0
1.2	14.377	0.98730557	0.99172625	0.99481210	0.99683848	0.99811472	0.99889505	0.99936165	0.99963573
2.6	85.949	0.99766488	0.99827059	0.99877487	0.99913184	0.99944272	0.99963846	0.99977047	0.99985715

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Phase C study.

The models for all test plans were revised to include the above flight by flight considerations to obtain the flight failure probabilities. Vibration reliability data were obtained for 9 component vibration test/design levels, 8 assembly test levels, and 3 shuttle acoustic environments for Test Plans 4, 6, 7, 8 after each level of testing. Note that the vibration reliability data for Test Plans 4, 7, and 8 also apply to Test Plans 5, 7B, and 9, respectively. This constitutes the basic data used to establish the probability of achieving a completely successful or partially successful flight. By combining the appropriate probabilities of flight and test failures with the various cost models, the expected program costs were estimated.

SECTION 3
PARAMETER STUDY

After the model revisions described in Section 2 were completed, a parameter study was made to determine the effects of the acoustic environment and of key parameter variations on alternate test plans and the associated test requirements. First, data for a revised baseline were obtained. Then the following parameters were varied:

1. Shuttle payload bay internal acoustic environment
2. STS launch cost
3. Degree of redundancy in the housekeeping section
4. Component retest/repair cost

A total of 196 cases were studied, seven conditions (baseline and 6 variations) for 4 payloads for 7 test plans. For each case data for the assembly test level yielding the minimum total expected cost of failure (TECF) were selected for the test plan evaluation. These items are discussed in the following subsections. To identify the data for the variations a case code, which is described in Section 3.1, was established.

3.1 CASE CODE

In order to identify the data generated for the 196 cases in the parameter study, a six-digit case code for the Phase C analysis was established. Each digit represents a particular parameter:

1st digit - Test Plan ID
- 1 = TP-4, Test Plan 4
- 2 = TP-5, Test Plan 5
- 3 = TP-6, Test Plan 6
- 4 = TP-7, Test Plan 7
- 5 = TP-7B, Test Plan 7B
- 6 = TP-8, Test Plan 8
- 7 = TP-9, Test Plan 9

2nd digit - Payload ID
1 = 1,2 Payload 1,2
2 = 1,6 Payload 1,6
3 = 7,2 Payload 7,2
4 = 7,6 Payload 7,6

3rd digit - Shuttle Payload Bay Internal Acoustic Environment ID
0 = Baseline
1 = 1st Variation
2 = 2nd Variation

4th digit - STS Launch Cost ID
0 = Baseline
1 = 1st Variation
2 = 2nd Variation

5th digit - Degree of Redundancy in Housekeeping Section ID
0 = Baseline
1 = 1st Variation

6th digit - Component Retest/Repair Cost ID
0 = Baseline
1 = 1st Variation

This case code was used throughout the Phase C analysis and is used in this report. It is the value given in the key to the symbols of the curves on the optimum cost graphs, Figures 4-1 to 4-28. The values used for the variations are given in the appropriate subsection. The test plans, given in Table 1-1, are described in Section 1. The payload ID gives the number of experiments (NEXP) and the number of components peculiar to an experiment (NCPE). For example, Payload 7,6 is the payload configuration that has 7 experiments with 6 components in each experiment.

In the discussion given in Section 4 a four-digit number is used in some places to indicate the variation being discussed. This number is the last four digits of the basic six-digit case code.

In this study only one parameter was varied at a time, so that in each case either three or four of the last four digits in the case code are zero. The following examples demonstrate the use of the case code.

1. 110000 - baseline data for Payload 1,2 of Test Plan 4.
2. 231000 - data for the first shuttle payload bay internal acoustic environment variation for Payload 7,2 of Test Plan 5.
3. 320200 - data for the second STS launch cost variation for Payload 1,6 of Test Plan 6.
4. 440010 - data for the first degree of redundancy variation for Payload 7,6 of Test Plan 7.
5. 630001 - data for the first component retest/repair cost variation for Payload 7,2 of Test Plan 8.

3.2 REVISED BASELINE

As a result of the model revisions described in Section 2, the computer programs developed to compute the probabilities and expected costs were changed. A significant portion of these programming changes was due to the modified group of test plans discussed in Section 1. The test plan changes for Phase C were as follows:

1. The addition of a no-test option (Test Plan 6).
2. The elimination of prototype components.
3. The testing of protoflight components at all levels of assembly.
4. The elimination of Structural Development Model (SDM) testing.

As in Phase B, Section 4.6 of Reference 2, the strength of the primary structure was considered to be influenced significantly by the selection of a design safety factor. Two design options were considered for the primary structure. In Test Plans 6 and 7 no structural test was considered and a design safety factor of 2.0 was used to assure a high structural reliability. In the remaining test plans of Phase C a protoflight structural test was used with a design safety factor of 1.5 to minimize the probability of failing the flight structure during testing at limit load. The flight reliabilities for the structure are summarized in Table 3-1. The probability of failures during protoflight structural testing was 0.04.

3.3 SHUTTLE PAYLOAD BAY INTERNAL ACOUSTIC ENVIRONMENT

The 145 dB shuttle payload bay internal acoustic spectrum of the STS Payload Accommodations document, Reference 1, was considered to represent the mean plus 2 sigma acoustic level as for Phase B, Section 2.1 of Reference 2. The shuttle payload acoustic environment is not completely defined; it depends on a number of factors such as the launch pad configuration, orbiter payload door structural configuration, door seal attenuation and the effects of vents. Current predictions vary from the 145 dB of the STS Payload Accommodations document. For Phase C the effects of the shuttle acoustic environment were examined by considering it as a variable covering a range about the current projections. The variation selected is representative of reductions that may be achieved by providing environmental controls and of increases that may be encountered due to prediction inaccuracies and unexpected phenomena. The variations considered for the Phase C study are:

1. Baseline - 145 dB OA
2. 1st Variation - 135 dB OA
3. 2nd Variation - 150 dB OA

The effects of the shuttle payload bay internal acoustic environment are discussed in detail in Section 4.3.1.

Table 3-1

Structure Reliability During Flight

Test Plan	Safety Factor	Flight Reliability	Remarks
1	2.00	0.99927	No structural test
1A	1.25	0.99875	Prototype SDM
2	1.50	0.999997	Protoflight
3	1.50	0.999997	Protoflight as part of system test
3A	1.25	0.99875	Prototype SDM
4	1.50	0.999997	Protoflight
5	1.50	0.999997	Protoflight as part of system test
6	2.00	0.99927	No structural test
7	2.00	0.99927	No structural test
7B	1.50	0.999997	Protoflight
8	1.50	0.999997	Protoflight
9	1.50	0.999997	Protoflight as part of system test

3.4 STS LAUNCH COST

The expected cost of flight failures includes the cost of incurring the loss of mission objectives during flight and the subsequent cost of refurbishing the payload after flight. The loss of data from each experiment is weighted equally so that a loss of a portion of the experiments during flight causes a corresponding portion of the single mission cost to be attributed to flight failures.

The cost of a complete loss of data is estimated to be equal to the cost of the flight. The flight cost attributable to this payload is estimated to be approximately 25 percent of the STS launch cost per flight, Section 5.2.5 of Reference 2. For Phase B the STS launch cost per flight was fixed at $13,500,000. In view of the current projections, for Phase C the effects of the STS launch cost per flight were examined by considering it as a variable representative of the current estimates for government or commercial launches The variations considered for the Phase C study are:

1. Baseline - $13,500,000 per flight
2. 1st Variation - $17,500,000 per flight
3. 2nd Variation - $21,500,000 per flight

The effects of the STS launch cost are discussed in Section 4.3.2.

3.5 REDUNDANCY IN HOUSEKEEPING SECTION

The probability of achieving the flight objectives is needed to determine the cost of flight failures. A component flight failure does not generally result in a complete loss of the payload. To determine the expected cost of a flight failure, the reliability model developed for Phase B, Section 4.7 of Reference 2, is used to estimate the probability of achieving a portion of the flight objectives.

The reliability model represents the payload system as a series of redundant components and a group of parallel experiments. The series components represent the basic subsystems used for housekeeping functions and are essential to the success of the flight. Each experiment is composed of a number of series components. Parameters of the model are the following:

NEXP = number of parallel experiments
NCPE = number of components peculiar to an experiment
NCCE = number of components common to all experiments, including the structure

Representative values for these parameters used in this study are:

NEXP = 1 and 7
NCPE = 2 and 6
NCCE = 17 (including the structure)

For Phase B the series of housekeeping components was considered to have single redundancy and the series of experiment components did not include any redundancy. For Phase C the effects of the degree of redundancy in the housekeeping section were examined by considering it as a variable. Again, no redundancy was considered for the components in the experiment section of the payload. The changes in the reliability due to changes in the degree of redundancy are demonstrated in Figure 3-1. In this figure the parameter RVC is the reliability of the component having no redundancy. The vibroacoustic reliability of the series components can be written as

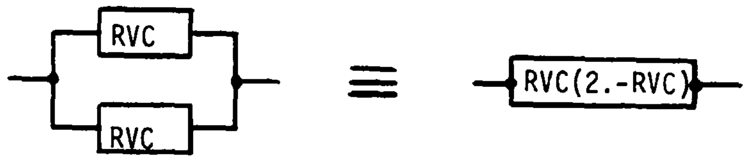
$$\prod_{1}^{NCCE} (R_C)_i = (RVS)\,\{RV\}^{NCCE-1} \tag{3-1}$$

where R_C = vibroacoustic reliability of a housekeeping component

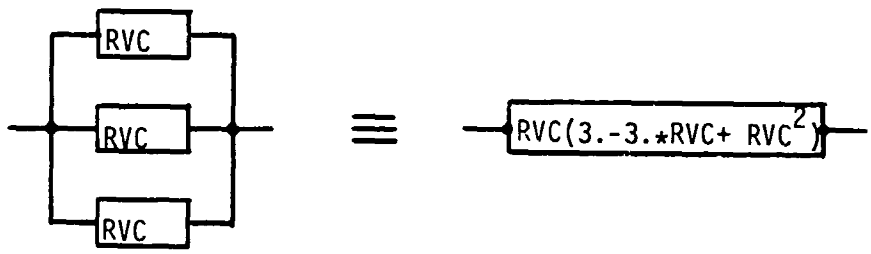
RVS = flight reliability of the structure

RV = vibroacoustic reliability of a redundant housekeeping component

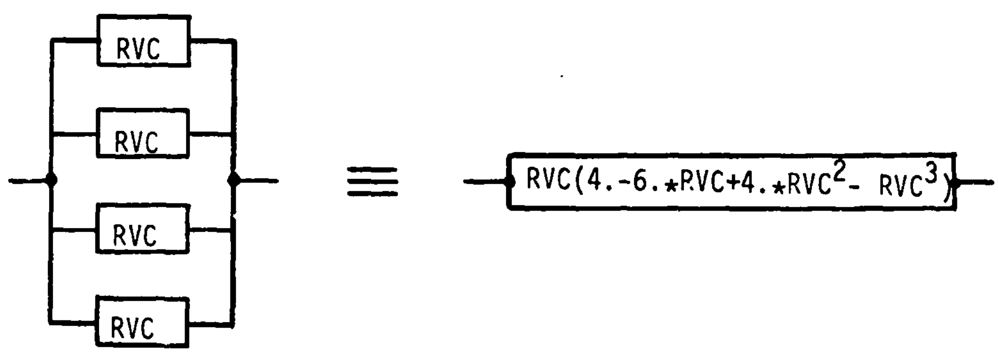
= values given in Figure 3-1



(a) Single Redundancy



(b) Double Redundancy



(c) Triple Redundancy

<u>Example</u> RVC = 0.9
R_a = 0.99
R_b = 0.999
R_c = 0.9999

Figure 3-1 Improving Reliabilities by Using Redundancy

The cost programs for all test plans were modified to handle degrees of redundancy of 0, 1, 2, 3. The variations considered for the Phase C study are:

1. Baseline - single redundancy
2. 1st Variation - double redundancy

The effects of the degree of redundancy are discussed in Section 4.3.3. The cost of purchasing the additional components when the degree of redundancy is varied was not included in this study.

3.6 COMPONENT RETEST/REPAIR COST

In accordance with present practices, any test or flight failure results in redesign and retest, so that the tests serve as a screen to remove marginal designs or hardware from the payload system. Testing at the component level of assembly is performed as a parallel project activity and the cost of component retest/redesign is based on the probability of a component failing the test. Subassembly testing is considered to be a parallel project activity for all payload subassemblies and for all but one experiment. Failures during subassembly testing are considered to be worked on a component basis using costs similar to those used for component testing. Failures during payload testing are considered to result in project schedule slippage with the related cost of the project team. The cost is related to the number of failures which occur with additional cost increases due to retesting at the component level of assembly. If a component malfunctions during flight, the payload is considered to be refurbished prior to the next flight. Payload refurbishment due to component failures is considered to consist of an additional functional test and the retest/repair of components at the component level of assembly.

The cost of redesigning and retesting a component after a failure occurs may increase during the assembly test and flight phases. Support from the component supplier may be required so that the cost is higher than it is during the component test phase. For Phase B this cost was fixed for all levels of testing. For Phase C the effects of the component retest/repair cost were examined by considering it as a variable covering a range of the current estimates. The variation selected is representative of the costs that may be incurred for failures occurring during the various test phases and flight.

The variations considered for the Phase C study are:

1. Baseline

Failure during component testing	$15,000
Failure during assembly testing	$15,000
Failure during flight	$15,000

2. 1st Variation

Failure during component testing	$15,000
Failure during assembly testing	$30,000
Failure during flight	$40,000

The effects of the component retest/repair cost are discussed in Section 4.3.4.

SECTION 4
TEST PLAN EVALUATION

The results obtained from applying the modified decision models to the seven vibroacoustic test plans of Phase C are presented and discussed in this section. The section is divided into three parts. The results obtained for the Phase C study are presented in Section 4.1. The revised baseline data are discussed in Section 4.2. The effects of the parameter variations are discussed in Section 4.3.

4.1 PHASE C RESULTS

The decision model for each test plan was exercised for four payload configurations. The payloads were of the facility type having 15 planned flights. The payload complexity was varied by considering either one or seven experiments. Each experiment was comprised of either two or six components. The housekeeping section of the payload was not changed and consisted of three subassemblies having a total of 16 redundant components and the structure.

Data were obtained for the 196 cases defined in Section 3.1. The identification of the data was aided considerably by the use of the case code described in Section 3.1. The values for the varied parameters are given in Tables 4-1 to 4-7 for the seven vibroacoustic test plans considered in Phase C. Each of these tables has four parts, one for each payload. For each payload values are given for each variation. Values are given for the case code, the mean plus 2 sigma sound pressure level of the shuttle payload bay internal acoustic environment, the STS launch cost, the degree of redundancy in the housekeeping section of the payload, and the retest/repair costs for failures that occur during test at the component and assembly levels of testing and during flight.

Table 4-1

Optimum Cost Data Summary
Test Plan 4
Protoflight Subassembly/Structure Testing

Code	Test Plan	Payload	Parameter: 2 Sigma SPL (dB)	Launch Cost ($x10^6)	Degree of Red'y	Retest/Repair Cost: Comp. ($x10^3)	Assembl. ($x10^3)	Flight ($x10^3)	Optimum: Expected Cost ($x10^6)	Standard. Vibration Variable	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Associated Vibroacoustic: Flight Failure Probability	Flight Reliability
110000	TP-4	1,2	145	13.5	1	15	15	15	0.988	1.900	19.767	151	0.00210	0.99790
111000			135	13.5	1	15	15	15	0.732	2.450	12.619	141	0.00082	0.99918
112000			150	13.5	1	15	15	15	1.208	1.[illegible]00	23.963	158	0.00185	0.99815
110100			145	17.5	1	15	15	15	1.154	1.950	21.071	1[illegible]3	0.00125	0.99875
110200			145	21.5	1	15	15	15	1.316	1.950	21.071	153	0.00125	0.99875
110010			145	13.5	2	15	15	15	1.078	1.850	18.544	151	0.00216	0.99784
110001			145	13.5	1	15	30	40	1.078	2.050	23.942	151	0.00186	0.99814
120000	TP-4	1,6	145	13.5	1	15	15	15	1.263	2.100	25.521	153	0.00334	0.99666
121000			135	13.5	1	15	15	15	0.840	2.650	16.292	143	0.00133	0.99867
122000			150	13.5	1	15	15	15	1.605	1.800	30.937	158	0.00489	0.99511
120100			145	17.5	1	15	15	15	1.454	2.100	25.521	155	0.00206	0.99794
120200			145	21.5	1	15	15	15	1.628	2.150	27.204	155	0.00199	0.99801
120010			145	13.5	2	15	15	15	1.376	2.000	22.461	153	0.00359	0.99641
120001			145	13.5	1	15	30	40	1.356	2.150	27.204	153	0.00323	0.99677
130000	TP-4	7,2	145	13.5	1	15	15	15	1.199	1.900	19.767	151	0.01448	0.98552
131000			135	13.5	1	15	15	15	0.882	2.450	12.619	141	0.00570	0.99430
132000			150	13.5	1	15	15	15	1.476	1.550	22.480	156	0.02195	0.97805
130100			145	17.5	1	15	15	15	1.374	1.900	19.767	151	0.01448	0.98552
130200			145	21.5	1	15	15	15	1.540	1.900	19.767	153	0.00897	0.99103
130010			145	13.5	2	15	15	15	1.287	1.850	18.544	151	0.01503	0.98497
130001			145	13.5	1	15	30	40	1.326	2.000	22.461	151	0.01340	0.98660
140000	TP-4	7,6	145	13.5	1	15	15	15	1.677	1.950	21.071	153	0.02573	0.97427
141000			135	13.5	1	15	15	15	1.052	2.500	13.451	141	0.01608	0.98392
142000			150	13.5	1	15	15	15	2.186	1.650	25.543	158	0.03669	0.96331
140100			145	17.5	1	15	15	15	1.877	1.950	21.071	153	0.02573	0.97427
140200			145	21.5	1	15	15	15	2.075	2.000	22.461	153	0.02484	0.97516
140010			145	13.5	2	15	15	15	1.780	1.900	19.767	153	0.02664	0.97336
140001			145	13.5	1	15	30	40	1.870	2.100	25.521	151	0.03667	0.96333

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Table 4-2

Optimum Cost Data Summary
Test Plan 5
Protoflight System/Structure Testing

Code	Test Plan	Payload	Parameter: 2 Sigma SPL (dB)	Parameter: Launch Cost ($x10^6)	Parameter: Degree of Red'y	Parameter: Retest/Repair Cost: Comp. ($x10^3)	Parameter: Retest/Repair Cost: Assembly ($x10^3)	Parameter: Retest/Repair Cost: Flight ($x10^3)	Optimum: Expected Cost ($x10^6)	Optimum: Standard. Vibration Variable	Optimum: Component Vibration Test/Design Level (g rms)	Optimum: Assembly Acoustic Test Level (dB)	Associated Vibroacoustic: Flight Failure Probability	Associated Vibroacoustic: Flight Reliability
210000	TP-5	1.2	145	13.5	1	15	15	15	1.469	2.250	30.910	147	0.00371	0.99629
211000			135	13.5	1	15	15	15	0.943	2.750	18.512	135	0.00149	0.99851
212000			150	13.5	1	15	15	15	1.947	1.900	35.152	154	0.00415	0.99585
210100			145	17.5	1	15	15	15	1.666	2.300	32.948	147	0.00354	0.99646
210200			145	21.5	1	15	15	15	1.853	2.300	32.948	149	0.00236	0.99764
210010			145	13.5	2	15	15	15	1.689	2.200	28.997	147	0.00383	0.99617
210001			145	13.5	1	15	30	40	1.505	2.300	32.948	147	0.00354	0.99646
220000	TP-5	1.6	145	13.5	1	15	15	15	1.818	2.350	35.121	149	0.00670	0.99330
221000			135	13.5	1	15	15	15	1.076	2.900	22.421	137	0.00274	0.99726
222000			150	13.5	1	15	15	15	2.438	1.950	37.470	156	0.00736	0.99264
220100			145	17.5	1	15	15	15	2.031	2.350	35.121	151	0.00438	0.99562
220200			145	21.5	1	15	15	15	2.240	2.350	35.121	151	0.00438	0.99562
220010			145	13.5	2	15	15	15	2.077	2.300	32.948	149	0.00698	0.99302
220001			145	13.5	1	15	30	40	1.838	2.350	35.121	151	0.00438	0.99562
230000	TP-5	7.2	145	13.5	1	15	15	15	1.668	2.250	30.910	145	0.03663	0.96337
231000			135	13.5	1	15	15	15	0.988	2.750	18.512	133	0.01301	0.98699
232000			150	13.5	1	15	15	15	2.284	1.900	35.152	152	0.04421	0.95579
230100			145	17.5	1	15	15	15	1.875	2.250	30.910	147	0.02534	0.97466
230200			145	21.5	1	15	15	15	2.073	2.300	32.948	147	0.02419	0.97581
230010			145	13.5	2	15	15	15	1.871	2.200	28.997	145	0.03841	0.96159
230001			145	13.5	1	15	30	40	1.727	2.250	30.910	147	0.02534	0.97466
240000	TP-5	7.6	145	13.5	1	15	15	15	2.449	2.250	30.910	149	0.04991	0.95009
241000			135	13.5	1	15	15	15	1.257	2.800	19.732	135	0.02847	0.97153
242000			150	13.5	1	15	15	15	3.465	1.900	35.152	154	0.08231	0.91769
240100			145	17.5	1	15	15	15	2.701	2.300	32.948	149	0.04784	0.95216
240200			145	21.5	1	15	15	15	2.950	2.300	32.948	149	0.04784	0.95216
240010			145	13.5	2	15	15	15	2.684	2.250	30.910	147	0.07397	0.92603
240001			145	13.5	1	15	30	40	2.503	2.250	30.910	149	0.04991	0.95009

Table 4-3

Optimum Cost Data Summary
Test Plan 6
No Testing

Code	Test Plan	Payload	Parameter						Optimum				Associated Vibroacoustic	
			2 Sigma SPL (dB)	Launch Cost ($x10^6)	Degree of Red.	Retest/Repair Cost			Expected Cost ($x10^6)	Standard. Vibration Variable	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Flight Failure Probability	Flight Reliability
						Comp. ($x10^3)	Assembly ($x10^3)	Flight ($x10^3)						
310000	TP-6	1,2	145	13.5	1	15	15	15	3.050	2.700	54.917	-	0.01982	0.98018
311000			135	13.5	1	15	15	15	1.630	3.050	27.155	-	0.00429	0.99571
312000			150	13.5	1	15	15	15	5.064	2.350	62.455	-	0.05459	0.94541
310100			145	17.5	1	15	15	15	3.710	2.700	54.917	-	0.01982	0.98018
310200			145	21.5	1	15	15	15	4.369	2.700	54.917	-	0.01982	0.98018
310010			145	13.5	2	15	15	15	3.375	2.550	45.342	-	0.02250	0.97750
310001			145	13.5	1	15	30	40	3.232	2.700	54.917	-	0.01982	0.98018
320000	TP-6	1,6	145	13.5	1	15	15	15	4.894	2.750	58.539	-	0.05115	0.94885
321000			135	13.5	1	15	15	15	2.008	3.200	32.890	-	0.00877	0.99123
322000			150	13.5	1	15	15	15	9.582	2.400	66.573	-	0.13184	0.86816
320100			145	17.5	1	15	15	15	6.038	2.750	58.539	-	0.05115	0.94885
320200			145	21.5	1	15	15	15	7.139	2.800	62.399	-	0.04801	0.95199
320010			145	13.5	2	15	15	15	5.324	2.750	58.539	-	0.05008	0.94992
320001			145	13.5	1	15	30	40	5.035	2.750	58.539	-	0.05115	0.94885
330000	TP-6	7,2	145	13.5	1	15	15	15	3.308	2.550	45.342	-	0.14501	0.85499
331000			135	13.5	1	15	15	15	1.743	3.000	25.475	-	0.02752	0.97248
332000			150	13.5	1	15	15	15	5.546	2.300	58.591	-	0.30014	0.69986
330100			145	17.5	1	15	15	15	4.000	2.700	54.917	-	0.12022	0.87978
330200			145	21.5	1	15	15	15	4.659	2.700	54.917	-	0.12022	0.87978
330010			145	13.5	2	15	15	15	3.604	2.550	45.342	-	0.14339	0.85661
330001			145	13.5	1	15	30	40	3.584	2.650	51.520	-	0.12788	0.87212
340000	TP-6	7,6	145	13.5	1	15	15	15	5.808	2.700	54.917	-	0.31634	0.68366
341000			135	13.5	1	15	15	15	2.261	3.100	28.946	-	0.06593	0.93407
342000			150	13.5	1	15	15	15	11.082	2.350	62.455	-	0.62932	0.37068
340100			145	17.5	1	15	15	15	7.001	2.700	54.917	-	0.31634	0.68366
340200			145	21.5	1	15	15	15	8.151	2.750	58.539	-	0.29973	0.70027
340010			145	13.5	2	15	15	15	6.190	2.700	54.917	-	0.31546	0.68454
340001			145	13.5	1	15	30	40	6.204	2.700	54.917	-	0.31634	0.68366

Table 4-4

Optimum Cost Data Summary
Test Plan 7
Protoflight Component Testing

			Parameter						Optimum				Associated Vibroacoustic	
						Retest/Repair Cost								
Code	Test Plan	Payload	2 Sigma SPL (dB)	Launch Cost ($x10^6$)	Degree of Red'y	Comp. ($x10^3$)	Assembly ($x10^3$)	Flight ($x10^3$)	Expected Cost ($x10^6$)	Standard. Vibration Variable	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Flight Failure Probability	Flight Reliability
410000	TP-7	1,2	145	13.5	1	15	15	15	3.655	2.400	37.437	-	0.01721	0.98279
411000			135	13.5	1	15	15	15	2.390	2.750	18.512	-	0.00527	0.99473
412000			150	13.5	1	15	15	15	5.151	2.150	48.375	-	0.03561	0.96439
410100			145	17.5	1	15	15	15	4.269	2.450	39.906	-	0.01564	0.98436
410200			145	21.5	1	15	15	15	4.860	2.500	42.537	-	0.01424	0.98576
410010			145	13.5	2	15	15	15	4.345	2.300	32.948	-	0.01940	0.98060
410001			145	13.5	1	15	30	40	3.810	2.450	39.906	-	0.01564	0.98436
420000	TP-7	1,6	145	13.5	1	15	15	15	5.148	2.600	48.333	-	0.03263	0.96737
421000			135	13.5	1	15	15	15	2.854	2.950	23.899	-	0.00950	0.99050
422000			150	13.5	1	15	15	15	7.926	2.350	62.455	-	0.06672	0.93328
420100			145	17.5	1	15	15	15	5.989	2.650	51.520	-	0.02961	0.97039
420200			145	21.5	1	15	15	15	6.775	2.700	54.917	-	0.02689	0.97311
420010			145	13.5	2	15	15	15	6.015	2.500	42.537	-	0.03880	0.96120
420001			145	13.5	1	15	30	40	5.268	2.600	48.333	-	0.03263	0.96737
430000	TP-7	7,2	145	13.5	1	15	15	15	4.182	2.350	35.121	-	0.11507	0.88493
431000			135	13.5	1	15	15	15	2.686	2.650	16.292	-	0.03859	0.96141
432000			150	13.5	1	15	15	15	5.939	2.100	45.383	-	0.21855	0.78145
430100			145	17.5	1	15	15	15	4.828	2.401	37.437	-	0.10532	0.89468
430200			145	21.5	1	15	15	15	5.450	2.450	39.906	-	0.09626	0.90374
430010			145	13.5	2	15	15	15	4.847	2.300	32.948	-	0.12426	0.87574
430001			145	13.5	1	15	30	10	4.417	2.350	35.121	-	0.11507	0.88493
440000	TP-7	7,6	145	13.5	1	15	15	15	7.020	2.450	39.906	-	0.25973	0.74027
441000			135	13.5	1	15	15	15	3.848	2.800	19.732	-	0.08187	0.91813
442000			150	13.5	1	15	15	15	10.782	2.250	54.966	-	0.42889	0.57111
440100			145	17.5	1	15	15	15	8.001	2.500	42.537	-	0.23920	0.76080
440200			145	21.5	1	15	15	15	8.934	2.550	45.342	-	0.21981	0.78019
440010			145	13.5	2	15	15	15	7.775	2.400	37.437	-	0.28071	0.71929
440001			145	13.5	1	15	30	10	7.314	2.500	42.537	-	0.23920	0.76080

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Table 4-5

Optimum Cost Data Summary
Test Plan 7B
Protoflight Component/Structure Testing

Code	Test Plan	Payload	Parameter						Optimum				Associated Vibroacoustic	
			2 Sigma SPL (dB)	Launch Cost ($x10⁶)	Degree of Red'y	Retest/Repair Cost			Expected Cost ($x10⁶)	Standard. Vibration Variable	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Flight Failure Probability	Flight Reliability
						Comp. ($x10³)	Assembl. ($x10³)	Flight ($x10³)						
510000	TP-7B	1,2	145	13.5	1	15	15	15	2.859	2.400	37.437	-	0.01649	0.98351
511000			135	13.5	1	15	15	15	1.602	2.750	18.512	-	0.00455	0.99545
512000			150	13.5	1	15	15	15	4.343	2.150	48.375	-	0.03491	0.96509
510100			145	17.5	1	15	15	15	3.229	2.450	39.906	-	0.01493	0.98507
510200			145	21.5	1	15	15	15	3.575	2.500	42.537	-	0.01352	0.98648
510010			145	13.5	2	15	15	15	3.547	2.300	32.948	-	0.01868	0.98132
510001			145	13.5	1	15	30	40	3.015	2.450	39.906	-	0.01493	0.98507
520000	TP-7B	1,6	145	13.5	1	15	15	15	4.339	2.600	48.333	-	0.03192	0.96808
521000			135	13.5	1	15	15	15	2.063	2.950	23.899	-	0.00878	0.99122
522000			150	13.5	1	15	15	15	7.092	2.350	62.455	-	0.06604	0.93396
520100			145	17.5	1	15	15	15	4.934	2.650	51.520	-	0.02891	0.97109
520200			145	21.5	1	15	15	15	5.474	2.700	54.917	-	0.02618	0.97382
520010			145	13.5	2	15	15	15	5.201	2.500	42.537	-	0.03810	0.96190
520001			145	13.5	1	15	30	40	4.460	2.600	48.333	-	0.03192	0.96808
530000	TP-7B	7,2	145	13.5	1	15	15	15	3.385	2.350	35.121	-	0.11443	0.88557
531000			135	13.5	1	15	15	15	1.899	2.650	16.292	-	0.03789	0.96211
532000			150	13.5	1	15	15	15	5.129	2.100	45.383	-	0.21798	0.78202
530100			145	17.5	1	15	15	15	3.786	2.400	37.437	-	0.10467	0.89533
530200			145	21.5	1	15	15	15	4.163	2.450	39.906	-	0.09560	0.90440
530010			145	13.5	2	15	15	15	4.047	2.250	30.910	-	0.13458	0.86542
530001			145	13.5	1	15	30	40	3.620	2.350	35.121	-	0.11443	0.88557
540000	TP-7B	7,6	145	13.5	1	15	15	15	6.204	2.450	39.906	-	0.25919	0.74081
541000			135	13.5	1	15	15	15	3.055	2.800	19.732	-	0.08120	0.91880
542000			150	13.5	1	15	15	15	9.938	2.250	54.966	-	0.42848	0.57152
540100			145	17.5	1	15	15	15	6.936	2.500	42.537	-	0.23865	0.76135
540200			145	21.5	1	15	15	15	7.622	2.550	45.342	-	0.21925	0.78075
540010			145	13.5	2	15	15	15	6.956	2.400	37.437	-	0.28018	0.71982
540001			145	13.5	1	15	30	40	6.501	2.500	42.537	-	0.23865	0.76135

Table 4-6

Optimum Cost Data Summary
Test Plan 8
Protoflight Component/Subassembly/Structure Testing

Code	Test Plan	Payload	Parameter: 2 Sigma SPL (dB)	Parameter: Launch Cost ($x10^6)	Parameter: Degree of Red'y	Parameter: Retest/Repair Cost: Comp. ($x10^3)	Parameter: Retest/Repair Cost: Assembly ($x10^3)	Parameter: Retest/Repair Cost: Flight ($x10^3)	Optimum: Expected Cost ($x10^6)	Optimum: Standard. Vibration Variable	Optimum: Component Vibration Test/Design Level (g rms)	Optimum: Assembly Acoustic Test Level (dB)	Associated Vibroacoustic: Flight Failure Probability	Associated Vibroacoustic: Flight Reliability
[illegible]	TP-8	1.2	145	13.5	1	15	15	15	1.683	1.550	12.642	153	0.00160	0.99840
611000			135	13.5	1	15	15	15	1.366	2.200	9.170	141	0.00109	0.99891
612000			150	13.5	1	15	15	15	1.923	1.350	17.413	158	0.00203	0.99797
610100			145	17.5	1	15	15	15	1.850	1.600	13.475	153	0.00154	0.99846
610200			145	21.5	1	15	15	15	2.016	1.600	13.475	153	0.00154	0.99846
610010			145	13.5	2	15	15	15	2.076	1.500	11.860	151	0.00274	0.99726
610001			145	13.5	1	15	30	40	1.806	1.750	16.321	151	0.00225	0.99775
620000	TP-8	1.6	145	13.5	1	15	15	15	2.090	1.750	16.321	153	0.00409	0.99591
621000			135	13.5	1	15	15	15	1.584	2.350	11.106	143	0.00180	0.99820
622000			150	13.5	1	15	15	15	2.450	1.400	18.561	160	0.00341	0.99[illegible]
620100			145	17.5	1	15	15	15	2.279	1.800	17.397	155	0.00238	0.99762
620200			145	21.5	1	15	15	15	2.459	1.800	17.397	155	0.00238	0.99762
620010			145	13.5	2	15	15	15	2.515	1.650	14.364	153	0.00441	0.99559
620001			145	13.5	1	15	30	40	2.212	1.850	18.544	153	0.00378	0.99622
630000	TP-8	7.2	145	13.5	1	15	15	15	2.129	1.550	12.642	151	0.01827	0.98173
631000			135	13.5	1	15	15	15	1.735	2.150	8.603	141	0.00798	0.99202
632000			150	13.5	1	15	15	15	2.442	1.300	16.335	156	0.02446	0.97554
630100			145	17.5	1	15	15	15	2.313	1.550	12.642	151	0.01827	0.98173
630200			145	21.5	1	15	15	15	2.480	1.550	12.642	153	0.01107	0.98893
630010			145	13.5	2	15	15	15	2.520	1.500	11.860	151	0.01898	0.98102
630001			145	13.5	1	15	30	40	2.305	1.700	15.311	151	0.01616	0.98384
640000	TP-8	7.6	145	13.5	1	15	15	15	3.214	1.600	13.475	153	0.03164	0.96836
641000			135	13.5	1	15	15	15	2.459	2.250	9.775	141	0.02124	0.97876
642000			150	13.5	1	15	15	15	3.762	1.350	17.413	158	0.04142	0.95858
640100			145	17.5	1	15	15	15	3.427	1.650	14.364	153	0.03049	0.96951
640200			145	21.5	1	15	15	15	3.637	1.650	14.364	153	0.03049	0.96951
640010			145	13.5	2	15	15	15	3.624	1.550	12.642	153	0.03280	0.96720
640001			145	13.5	1	15	30	40	3.491	1.800	17.397	151	0.04384	0.95616

Table 4-7

Optimum Cost Data Summary
Test Plan 9
Protoflight Component/System/Structure Testing

Code	Test Plan	Payload	Parameter: 2 Sigma SPL (dB)	Parameter: Launch Cost ($x10^6$)	Parameter: Degree of Red'y	Parameter: Retest/Repair Cost: Comp. ($x10^3$)	Parameter: Retest/Repair Cost: Assembly ($x10^3$)	Parameter: Retest/Repair Cost: Flight ($x10^3$)	Optimum: Expected Cost ($x10^6$)	Optimum: Standard. Vibration Variable	Optimum: Component Vibration Test/Design Level (g rms)	Optimum: Assembly Acoustic Test Level (dB)	Associated Vibroacoustic: Flight Failure Probability	Associated Vibroacoustic: Flight Reliability
710000	TP-9	1,2	145	13.5	1	15	15	15	2.279	1.950	21.071	147	0.00459	0.99541
711000			135	13.5	1	15	15	15	1.647	2.500	13.451	135	0.00220	0.99780
712000			150	13.5	1	15	15	15	2.802	1.650	25.543	154	0.00452	0.99548
710100			145	17.5	1	15	15	15	2.484	1.950	21.071	149	0.00297	0.99703
710200			145	21.5	1	15	15	15	2.671	2.000	22.461	149	0.00283	0.99717
710010			145	13.5	2	15	15	15	2.852	1.906	19.767	147	0.00476	0.99524
710001			145	13.5	1	15	30	40	2.325	2.000	22.461	147	0.00435	0.99565
720000	TP-9	1,6	145	13.5	1	15	15	15	2.751	2.050	23.942	151	0.00510	0.99490
721000			135	13.5	1	15	15	15	1.900	2.600	15.284	139	0.00292	0.99708
722000			150	13.5	1	15	15	15	3.403	1.750	29.023	156	0.00756	0.99244
720100			145	17.5	1	15	15	15	2.971	2.100	25.521	151	0.00486	0.99514
720200			145	21.5	1	15	15	15	3.187	2.100	25.521	151	0.00486	0.99514
720010			145	13.5	2	15	15	15	3.387	2.000	22.461	149	0.00835	0.99165
720001			145	13.5	1	15	30	40	2.770	2.050	23.942	151	0.00510	0.99490
730000	TP-9	7,2	145	13.5	1	15	15	15	2.764	1.950	21.071	147	0.03123	0.96877
731000			135	13.5	1	15	15	15	1.934	2.450	12.619	135	0.01635	0.98365
732000			150	13.5	1	15	15	15	3.443	1.650	25.543	152	0.04867	0.95133
730100			145	17.5	1	15	15	15	2.976	1.950	21.071	147	0.03123	0.96877
730200			145	21.5	1	15	15	15	3.186	2.000	22.461	147	0.02958	0.97042
730010			145	13.5	2	15	15	15	3.327	1.900	19.767	145	0.04881	0.95119
730001			145	13.5	1	15	30	40	2.826	1.950	21.071	147	0.03123	0.96877
740000	TP-9	7,6	145	13.5	1	15	15	15	4.211	1.950	21.071	149	0.05990	0.94010
741000			135	13.5	1	15	15	15	2.812	2.500	13.451	137	0.03272	0.96728
742000			150	13.5	1	15	15	15	5.336	1.700	27.228	154	0.08575	0.91425
740100			145	17.5	1	15	15	15	4.496	2.000	22.461	149	0.05704	0.94296
740200			145	21.5	1	15	15	15	4.755	2.000	22.461	151	0.03672	0.96328
740010			145	13.5	2	15	15	15	4.822	1.950	21.071	149	0.05987	0.94013
740001			145	13.5	1	15	30	40	4.276	1.950	21.071	149	0.05990	0.94010

For each case the component vibration test/design level in g rms and the assembly acoustic test level in dB were varied. The range of the component level was fixed in terms of the standardized vibration variable, U_V; nine values were selected. The range of the assembly level was fixed in terms of the mean, μ, and the standard deviation, σ, of the acoustic environment; eight values were selected. The results are given in the Addendum. The total of the expected costs of failures and the direct costs, TECF, expressed in millions of dollars, and the flight failure probability, FFP, i.e., the probability of losing experiment data during flight, are presented.

The optimum data given in the TECF tables are summarized in Tables 4-1 to 4-7 for the seven test plans considered in Phase C. Each table gives the data for each variation of the four payload configurations studied. Values are given for the optimum expected cost in millions of dollars. The standardized vibration variable, the component vibration test/design level, in g rms, and the assembly acoustic test level, in dB, at which the optimum cost occurs are given. Also given are the associated vibroacoustic flight failure probability and flight reliability; the sum of these two parameters is 1.0.

The TECF data for the assembly test level at which the optimum cost occurs are shown in Figures 4-1 to 4-28. These figures show the expected cost in millions of dollars versus the component vibration test level or design level in g rms. Each figure shows the seven variations for one test plan/payload combination. The symbols used on the curves are identified according to the six-digit case code presented in Section 3.1. The data plotted on these figures were taken from the expanded TECF tables discussed in the Addendum. Note that optimum vibration test levels are clearly evident for all

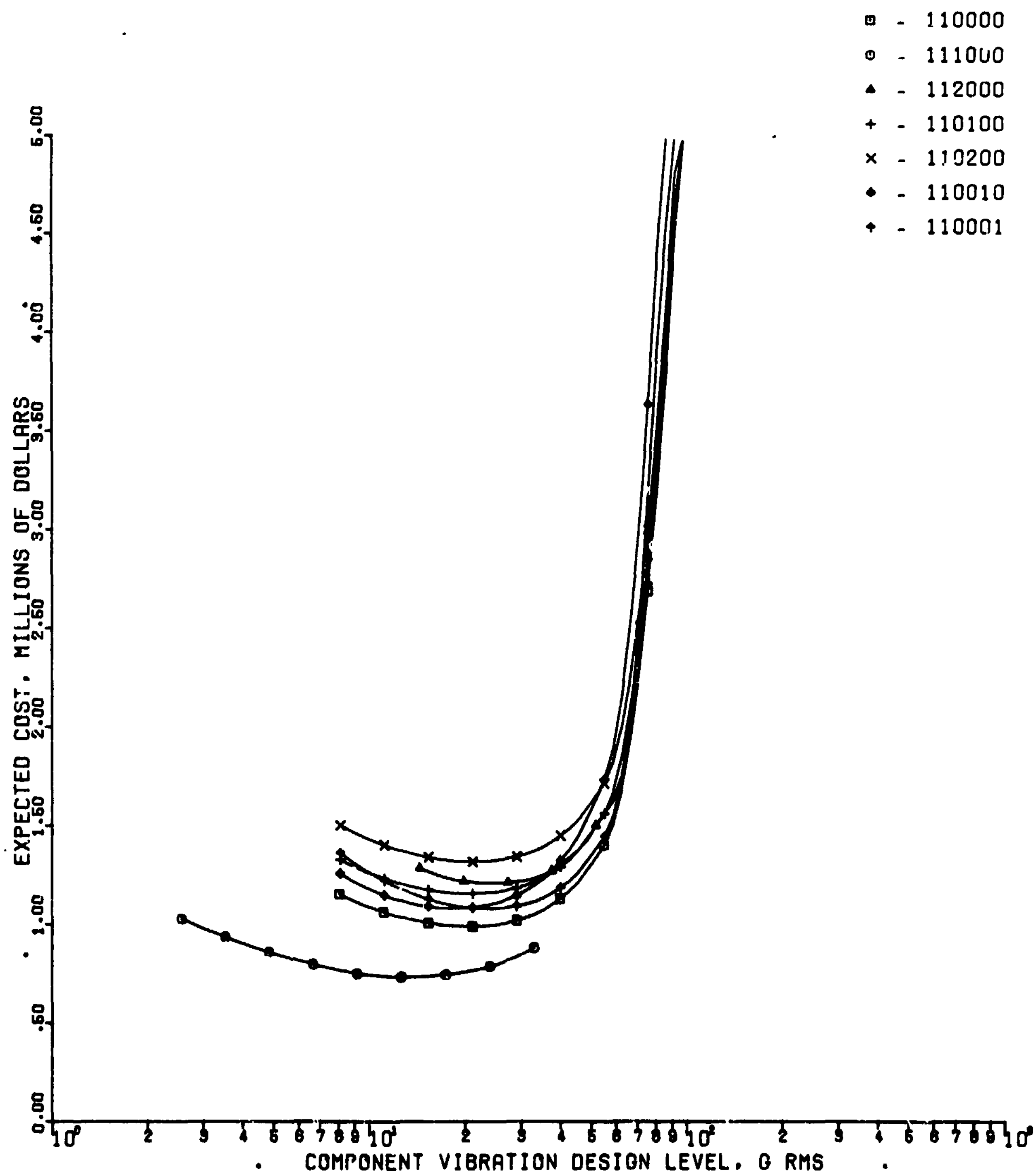

Figure 4-1 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 4, Payload 1,2

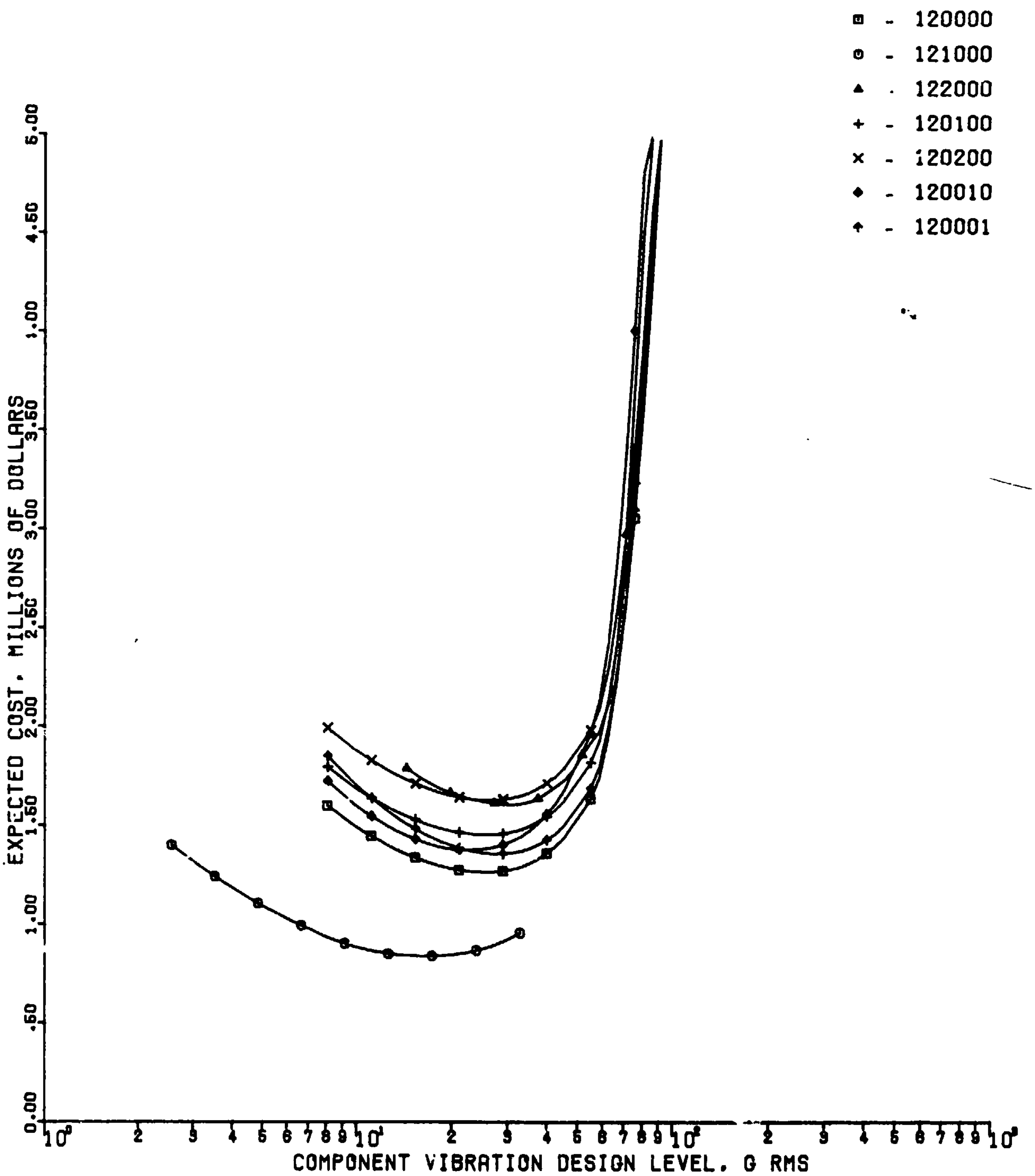

Figure 4-2 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 4, Payload 1,6

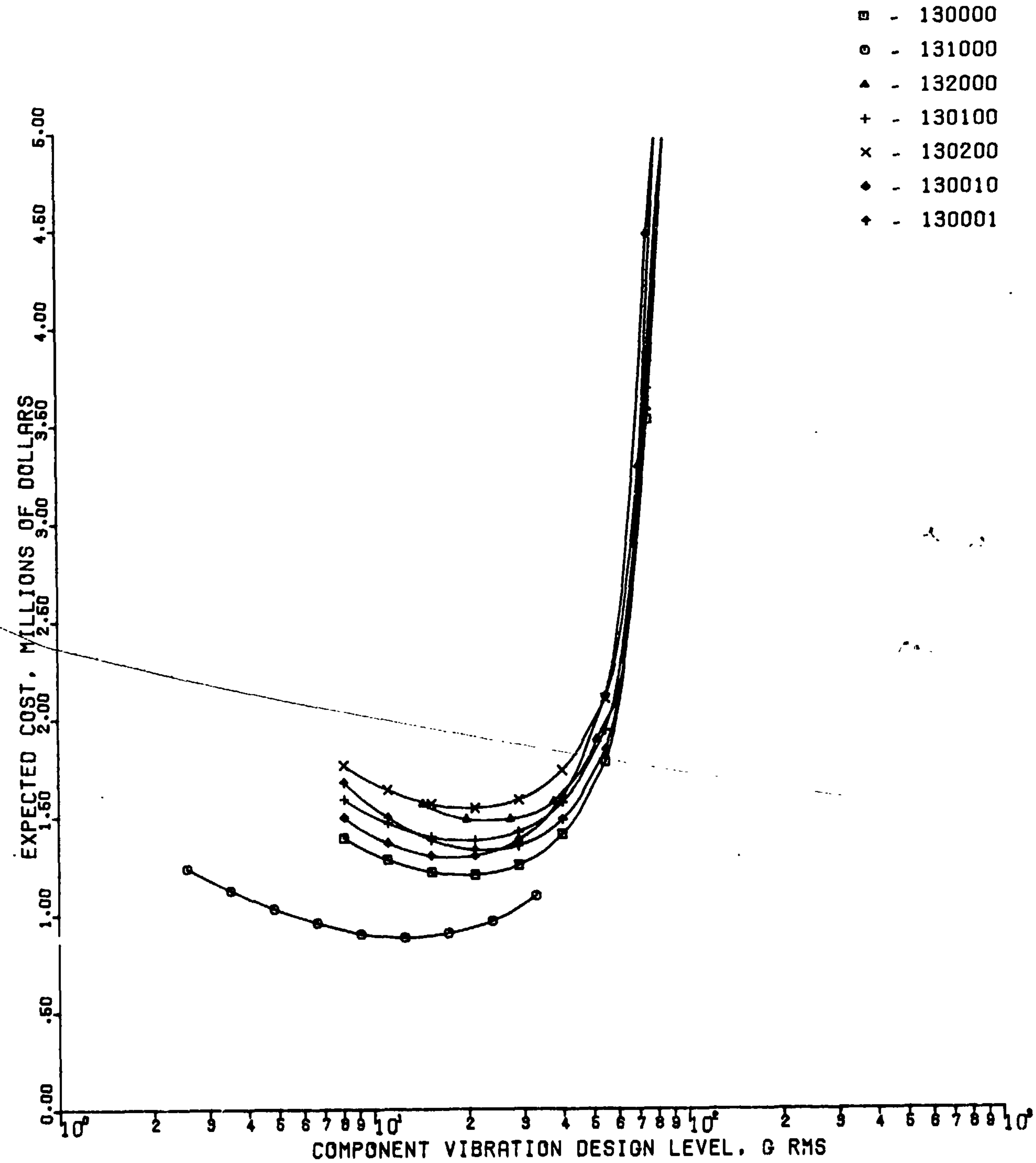

Figure 4-3 Costs for Optimum Acoustic Test Levels
Test Plan 4, Payload 7,2

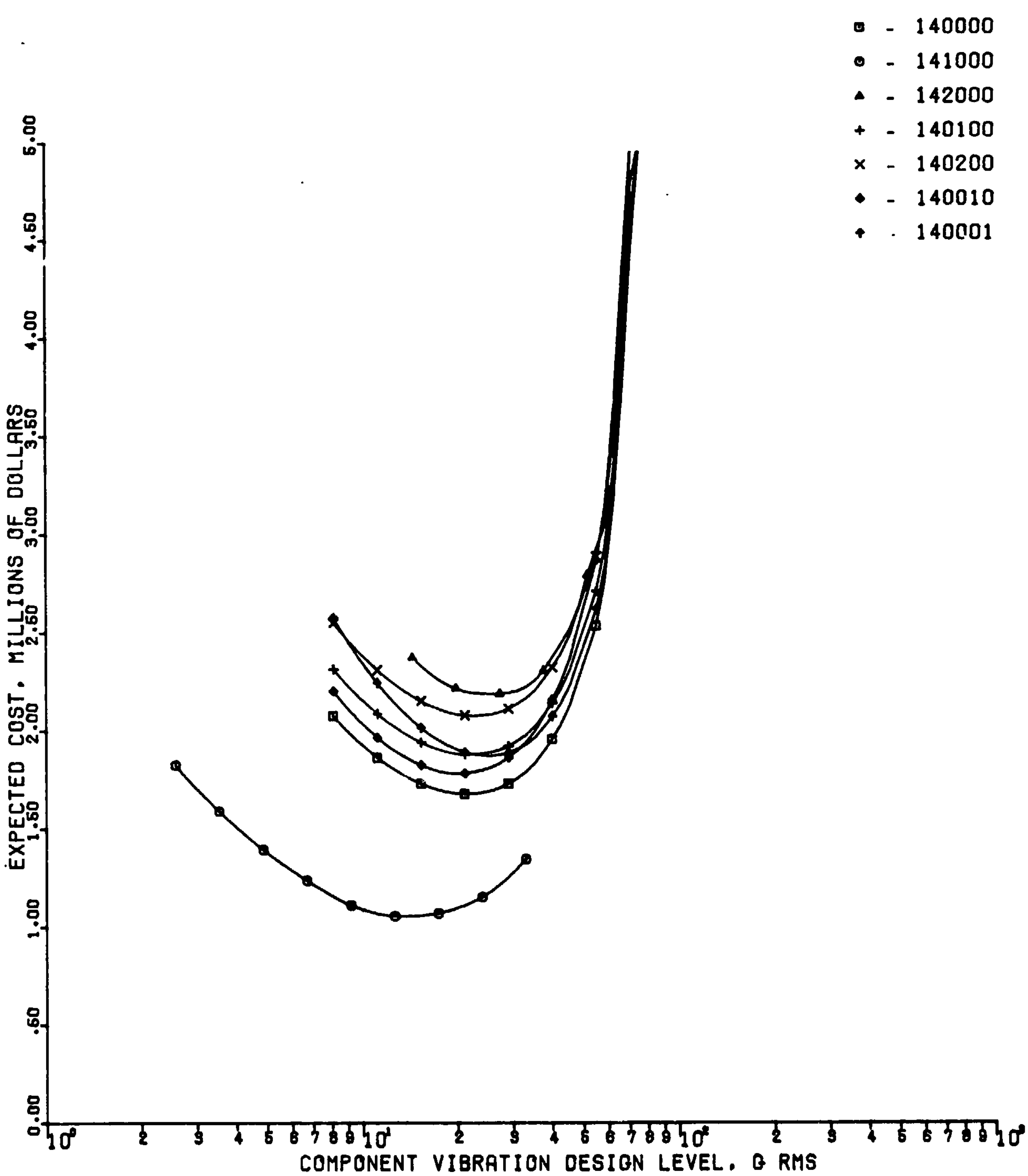

Figure 4-4 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 4, Payload 7,6

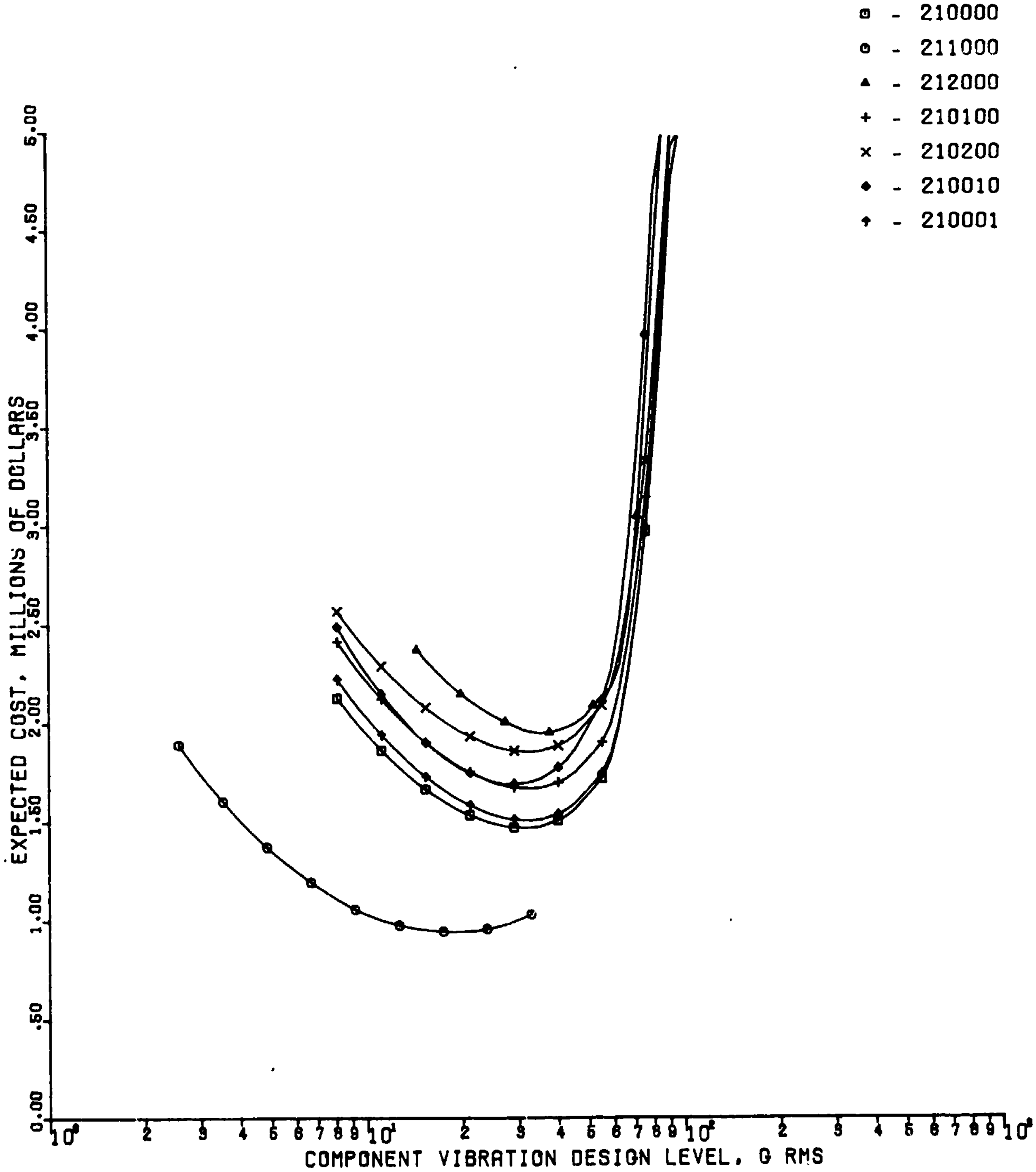

Figure 4-5 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 5, Payload 1.2

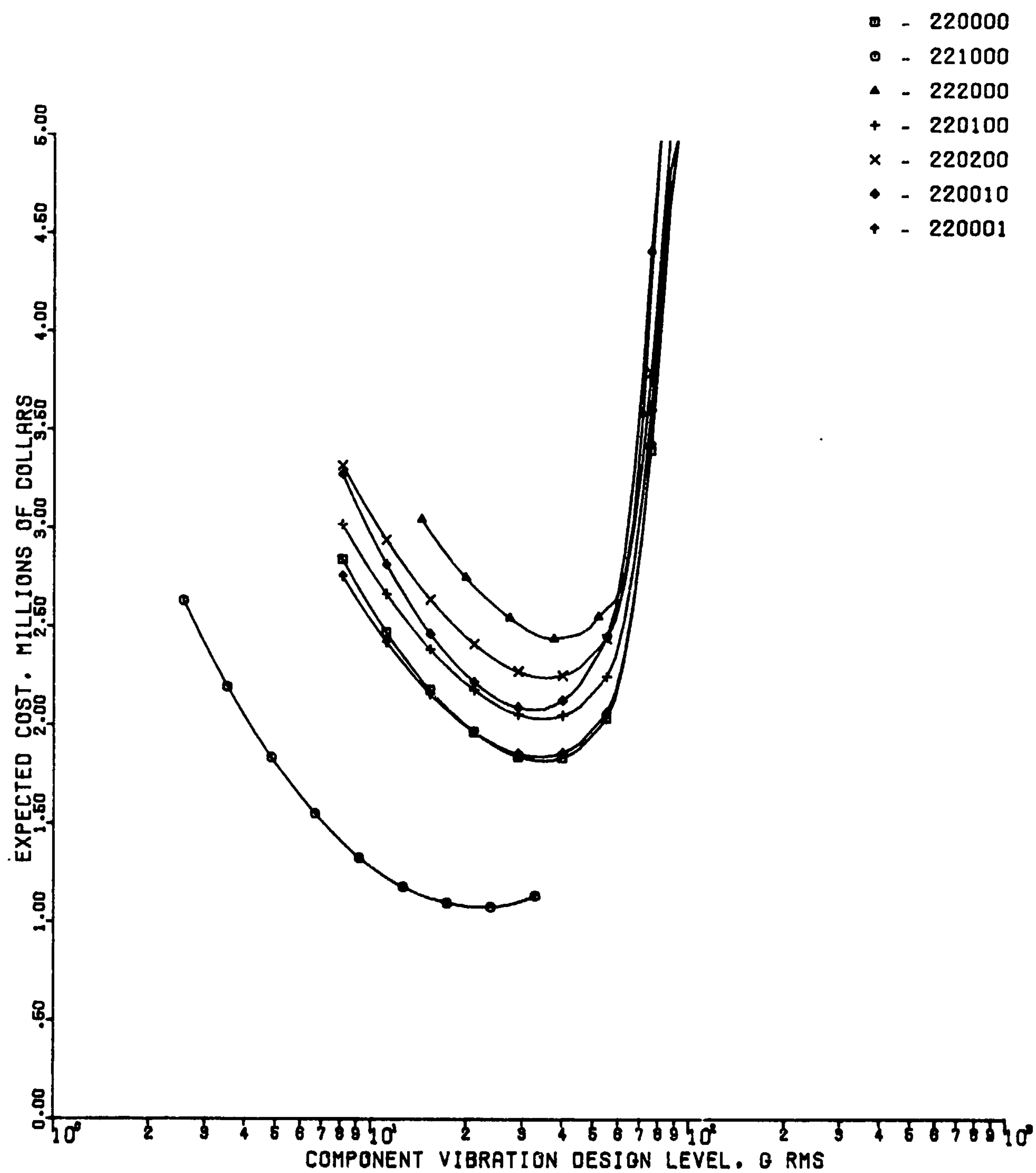

Figure 4-6 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 5, Payload 1,6

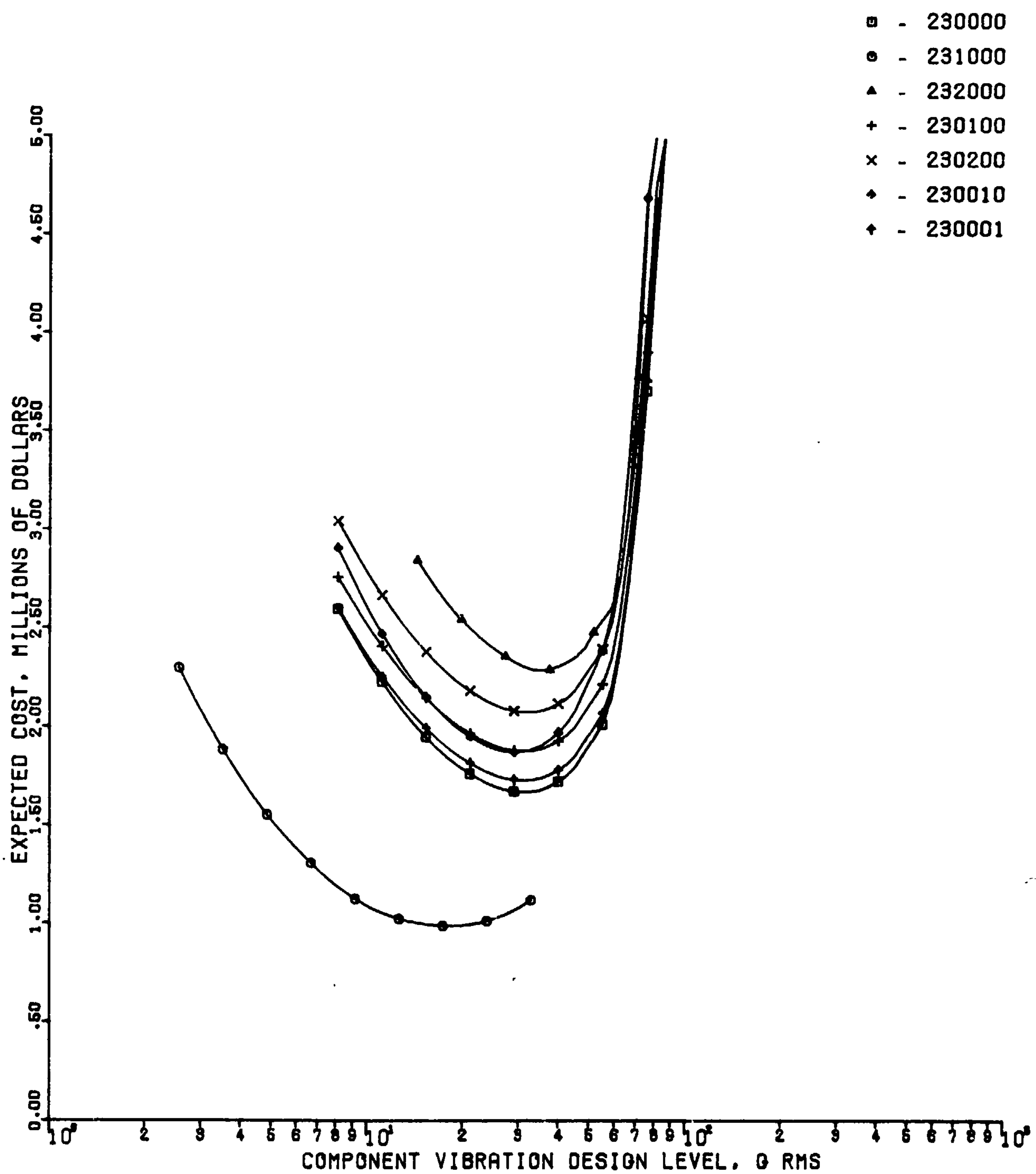

Figure 4-7 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 5, Payload 7,2

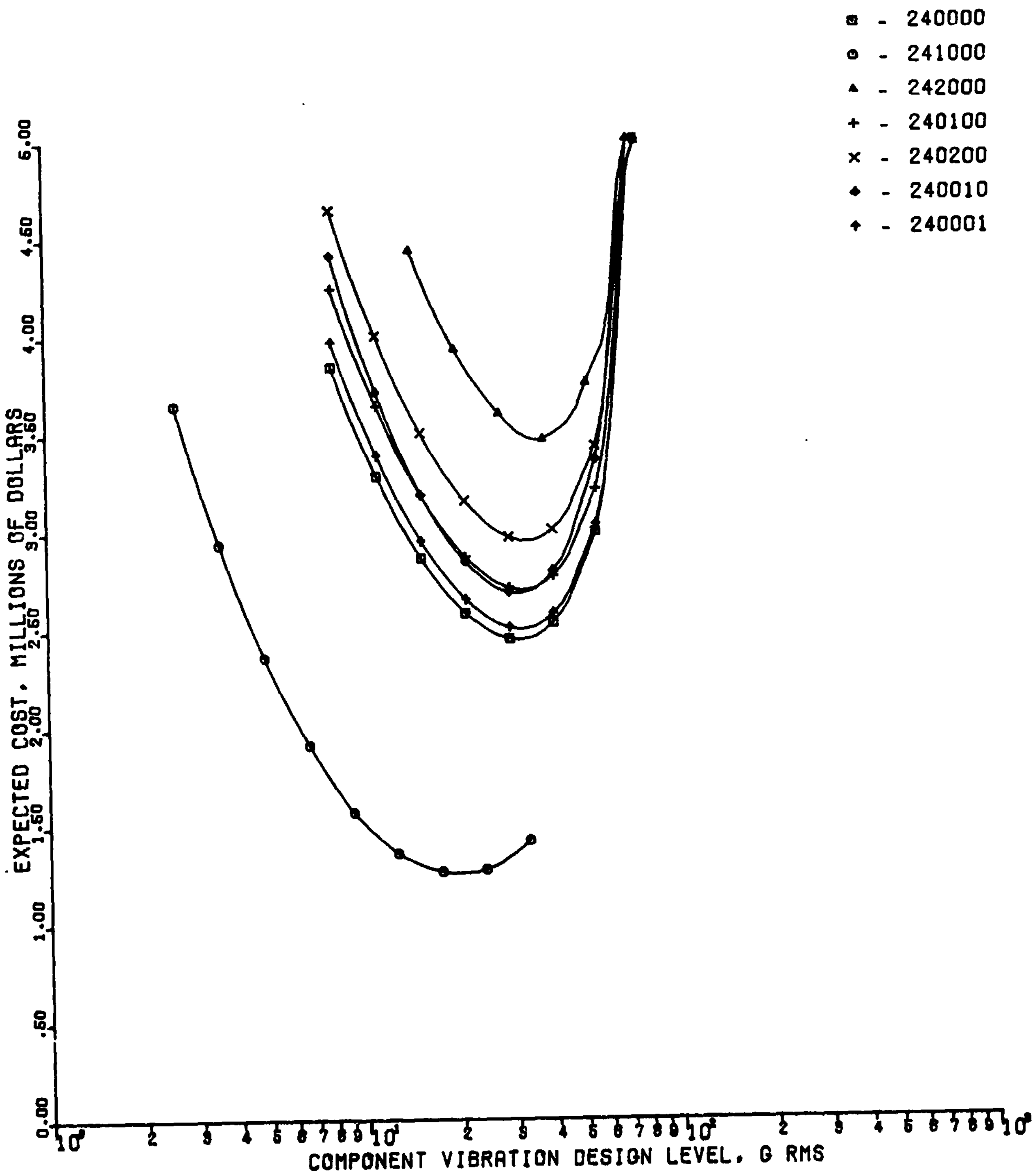

Figure 4-8 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 5, Payload 7.6

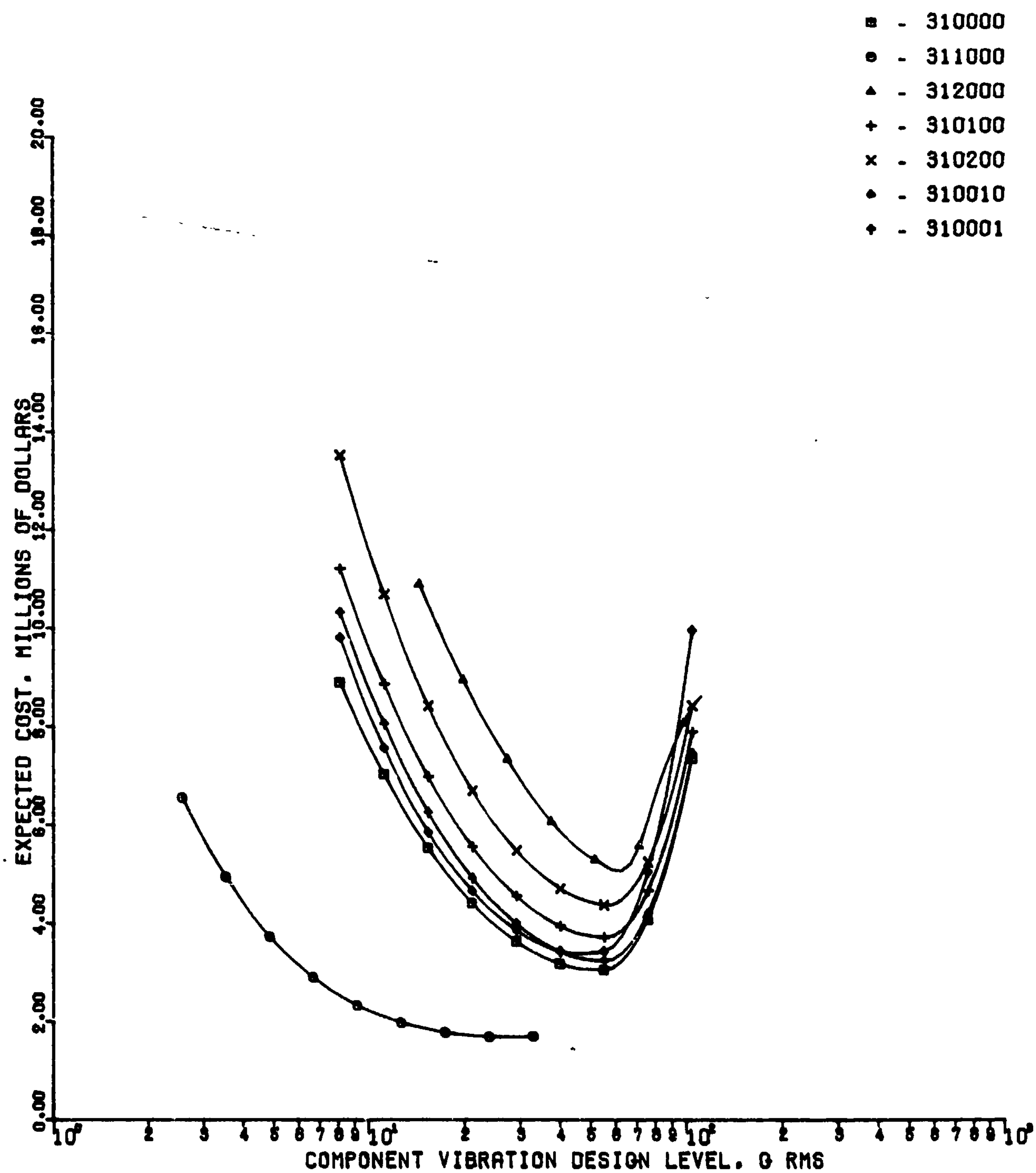

Figure 4-9 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 6, Payload 1,2

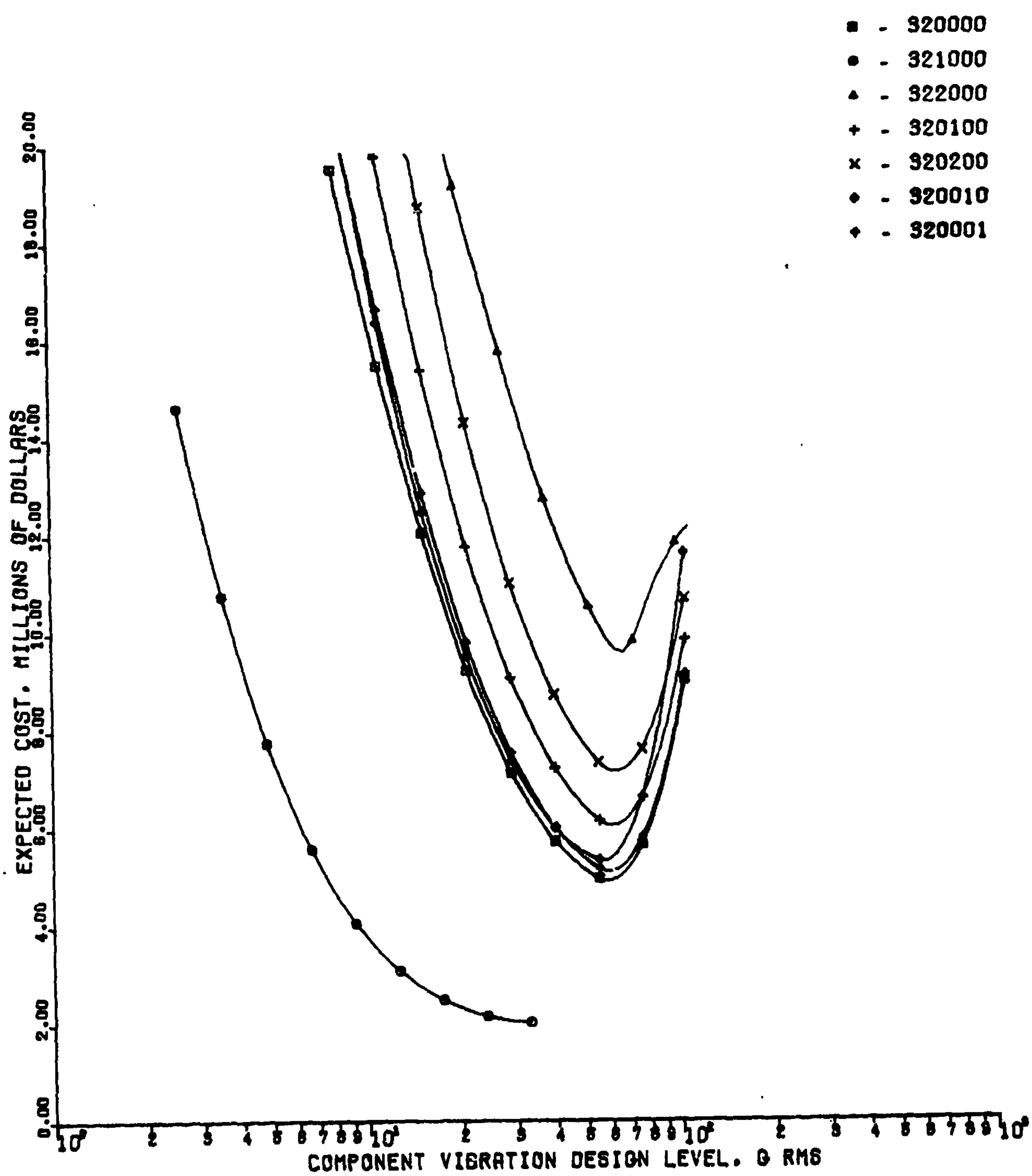

Figure 4-10 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 6, Payload 1,6

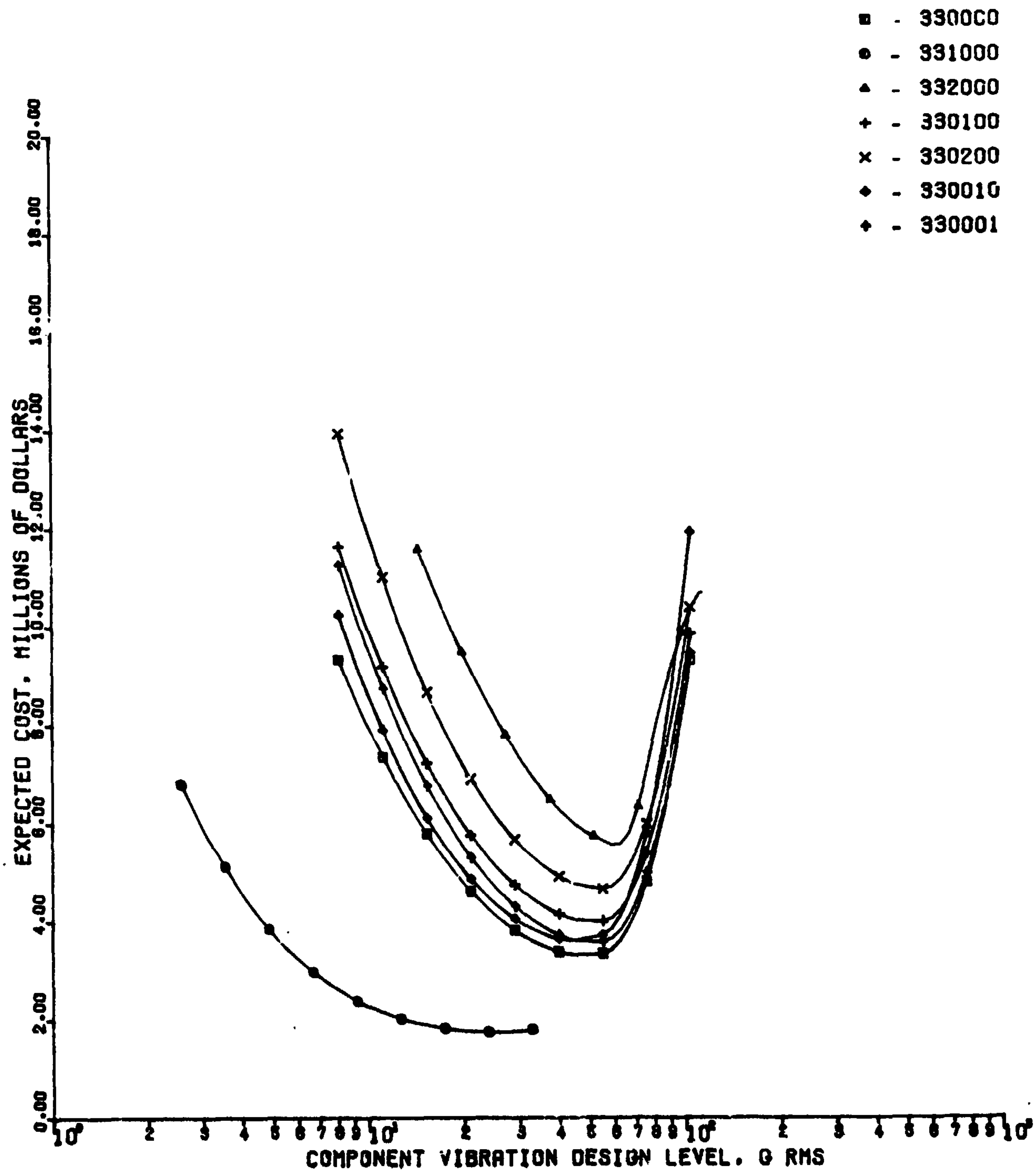

Figure 4-11 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 6, Payload 7,2

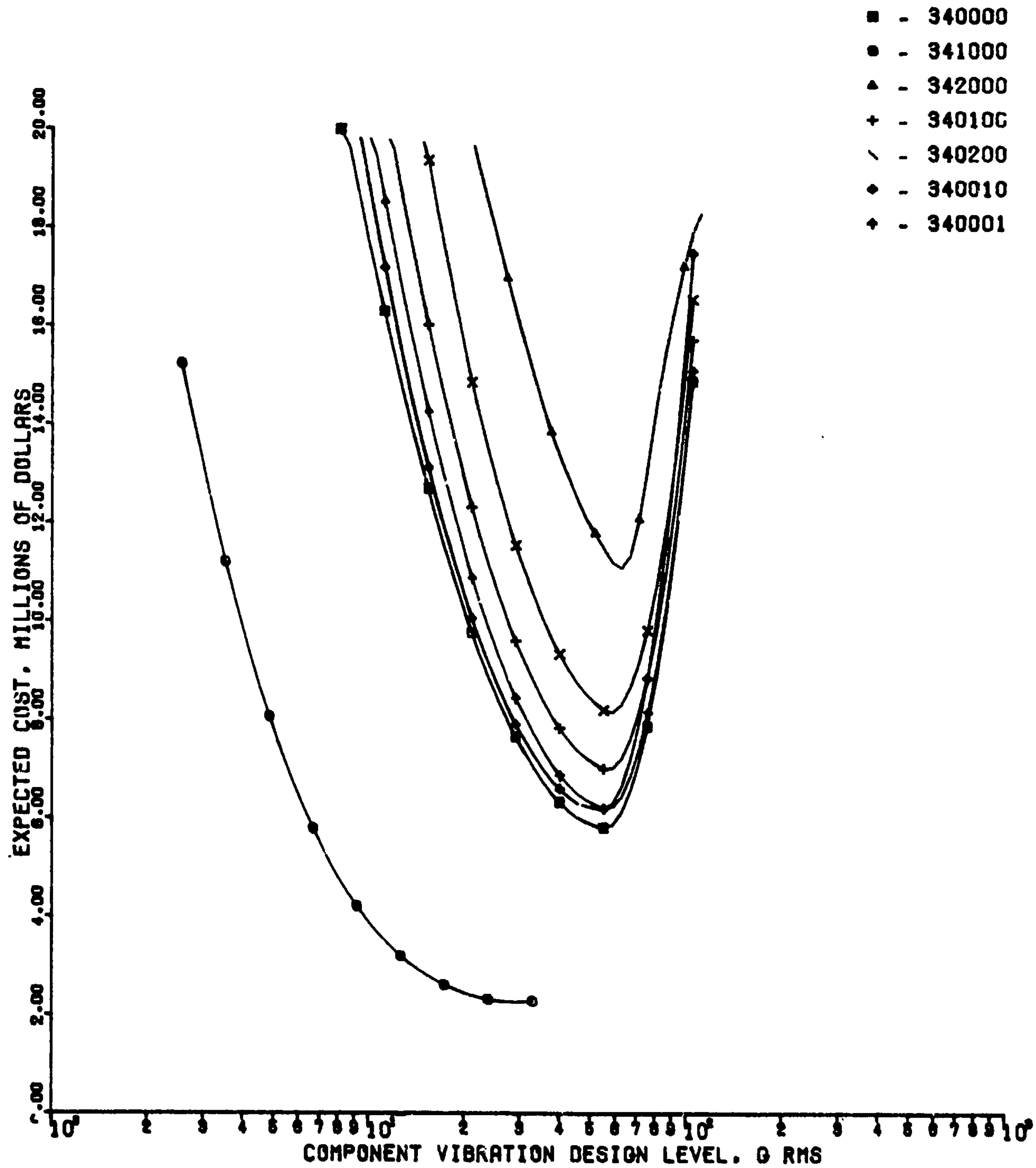

Figure 4-12 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 6, Payload 7,6

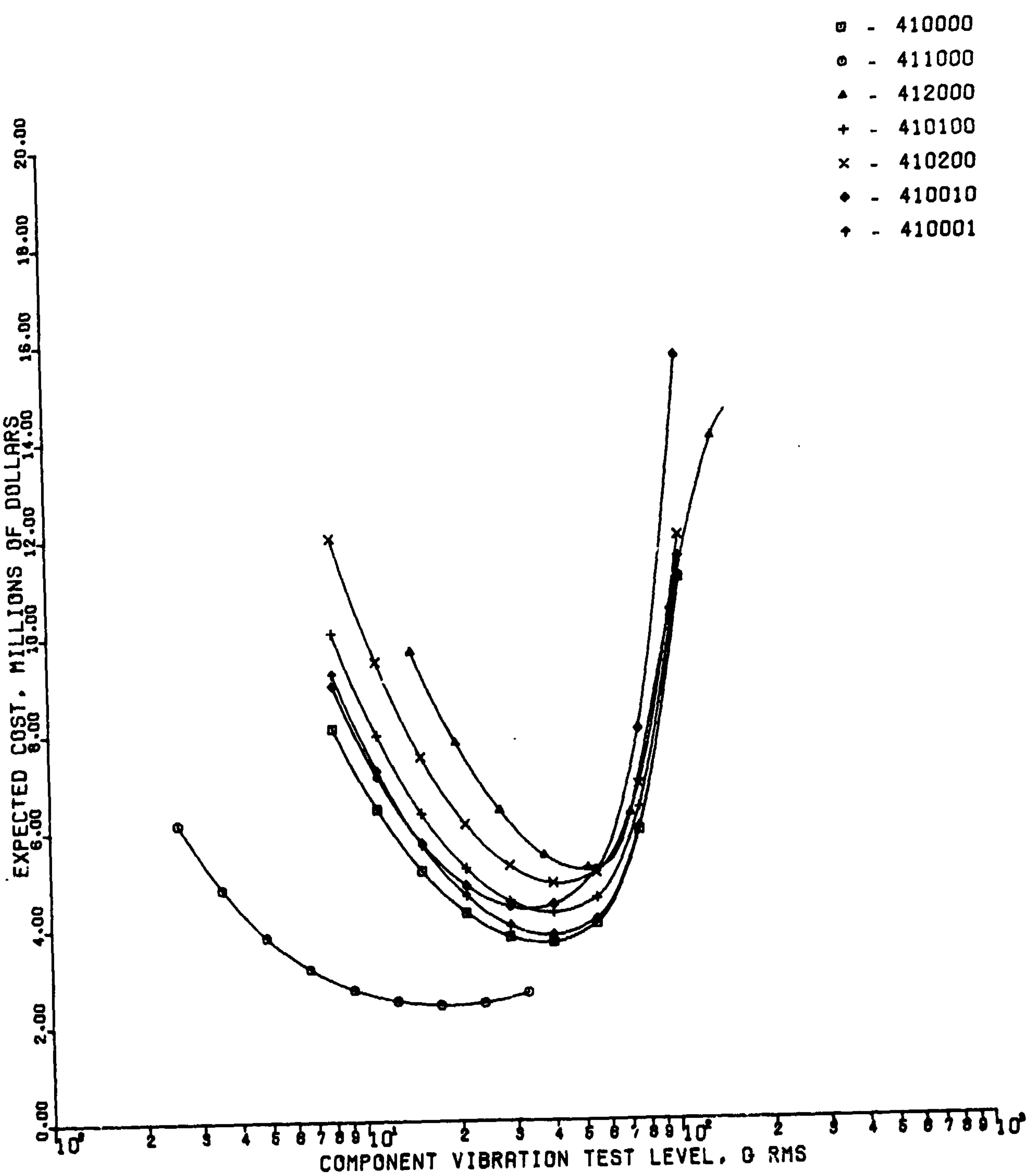

Figure 4-13 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 7, Payload 1,2

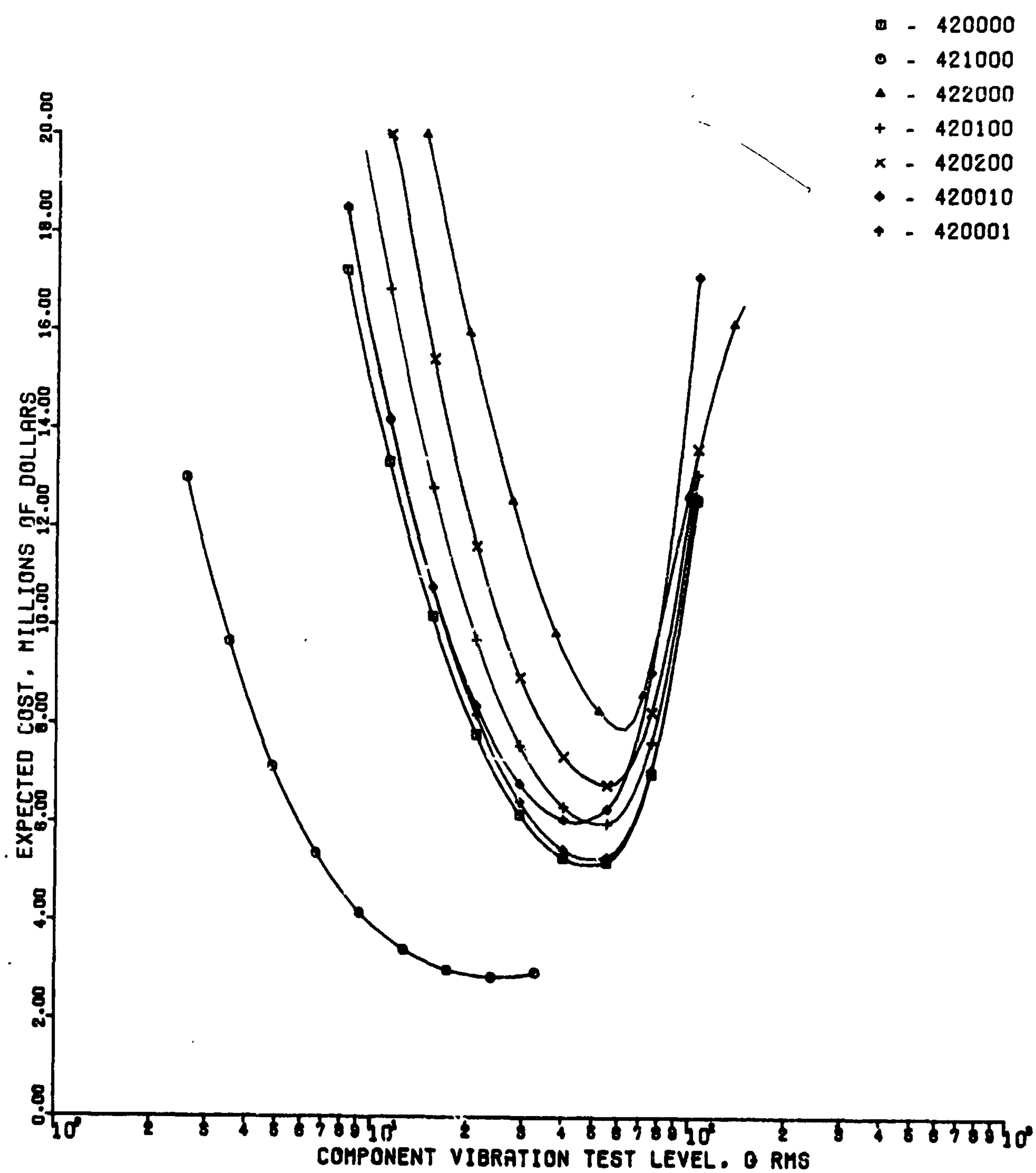

Figure 4-14 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 7, Payload 1,6

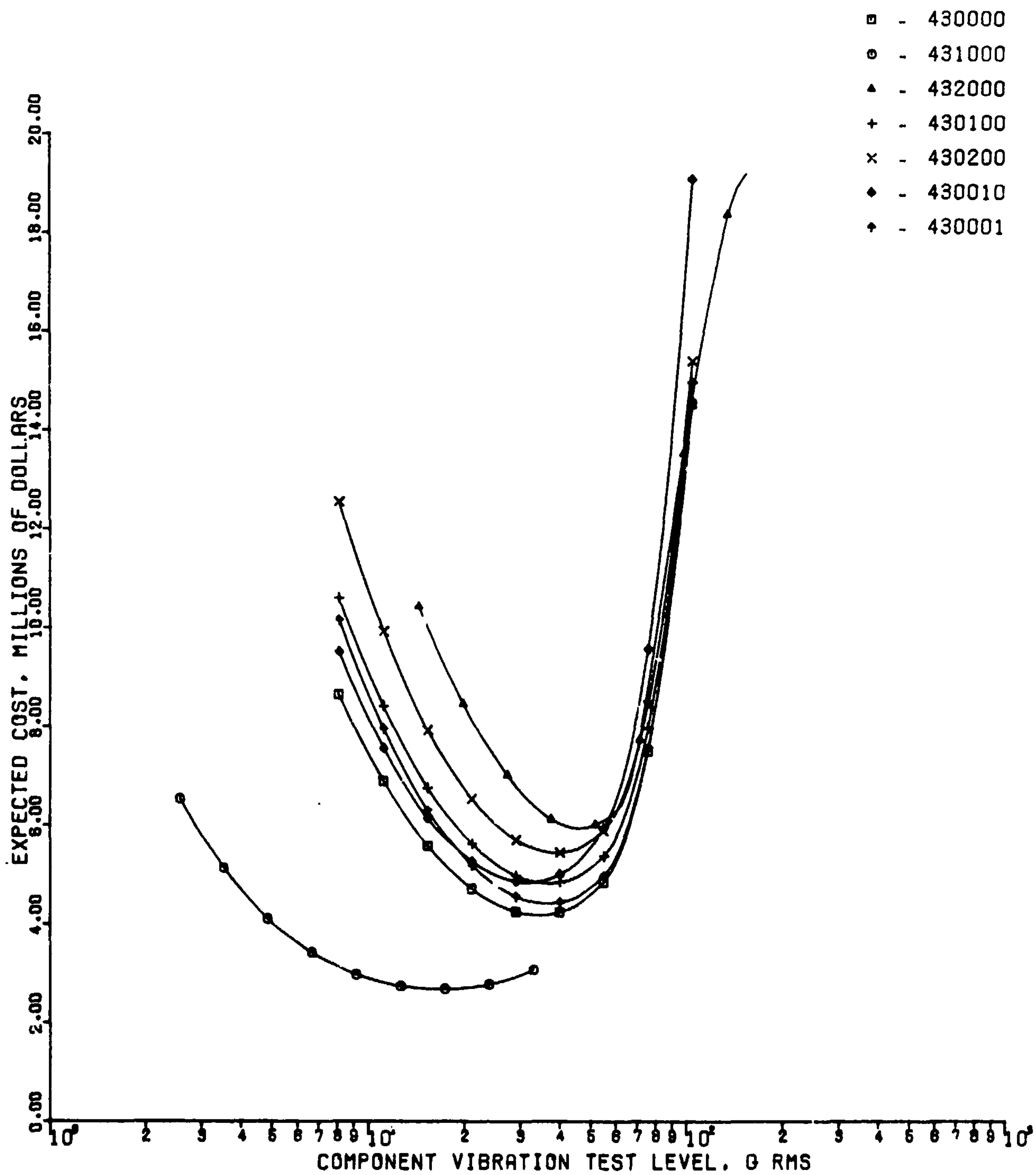

Figure 4-15 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 7, Payload 7,2

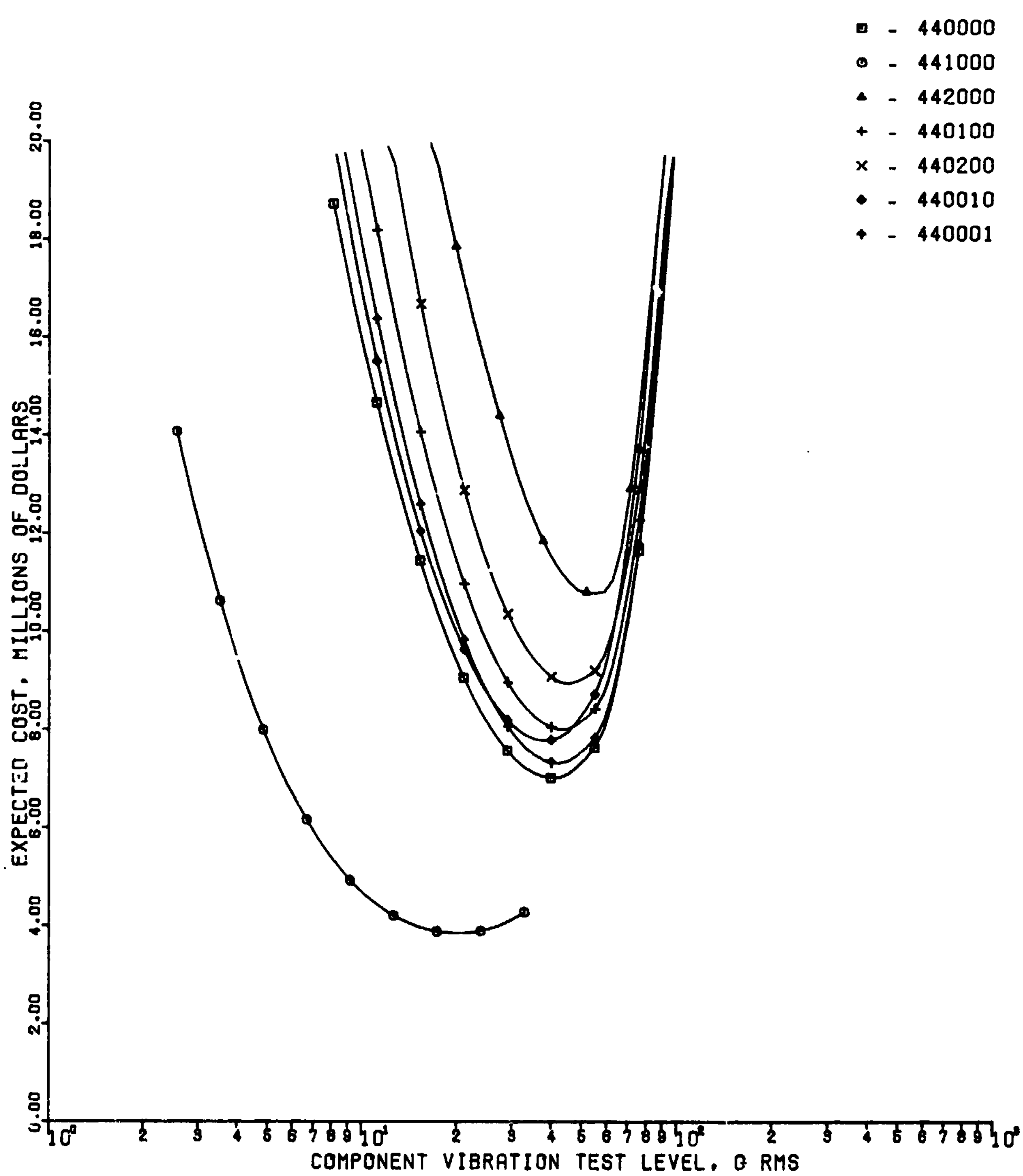

Figure 4-16 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 7, Payload 7,6

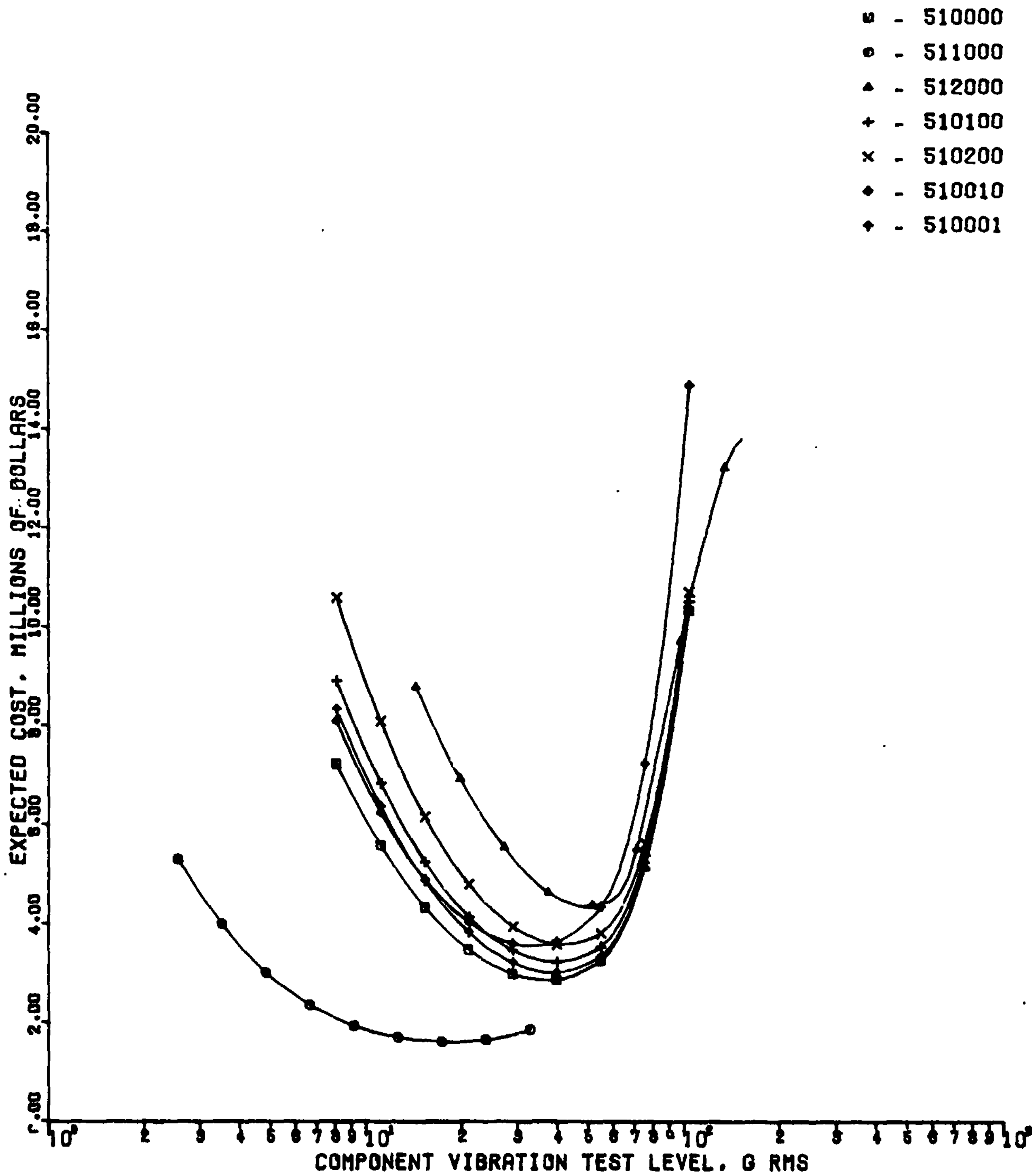

Figure 4-17 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 7B, Payload 1,2

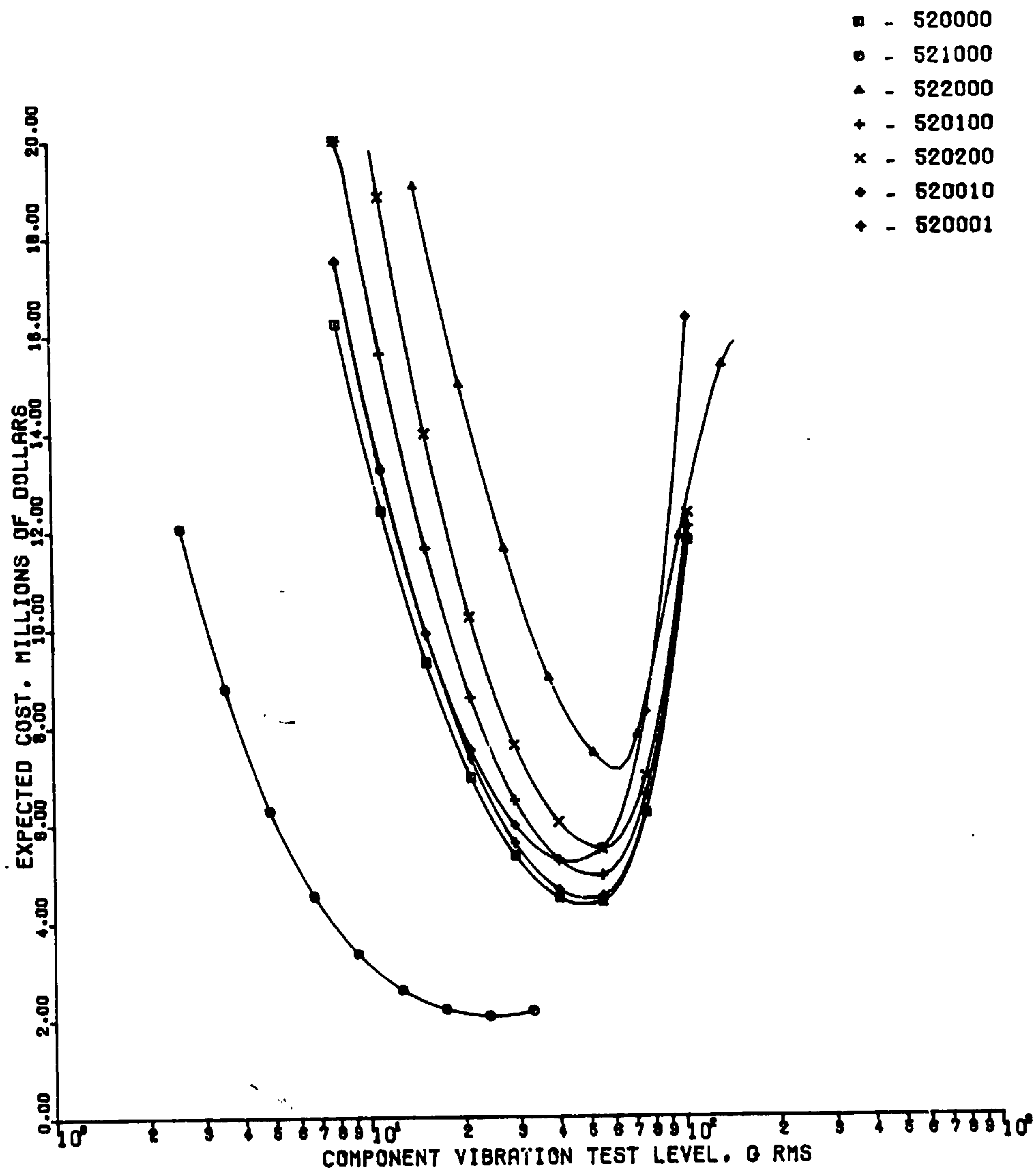

Figure 4-18 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 7B, Payload 1,6

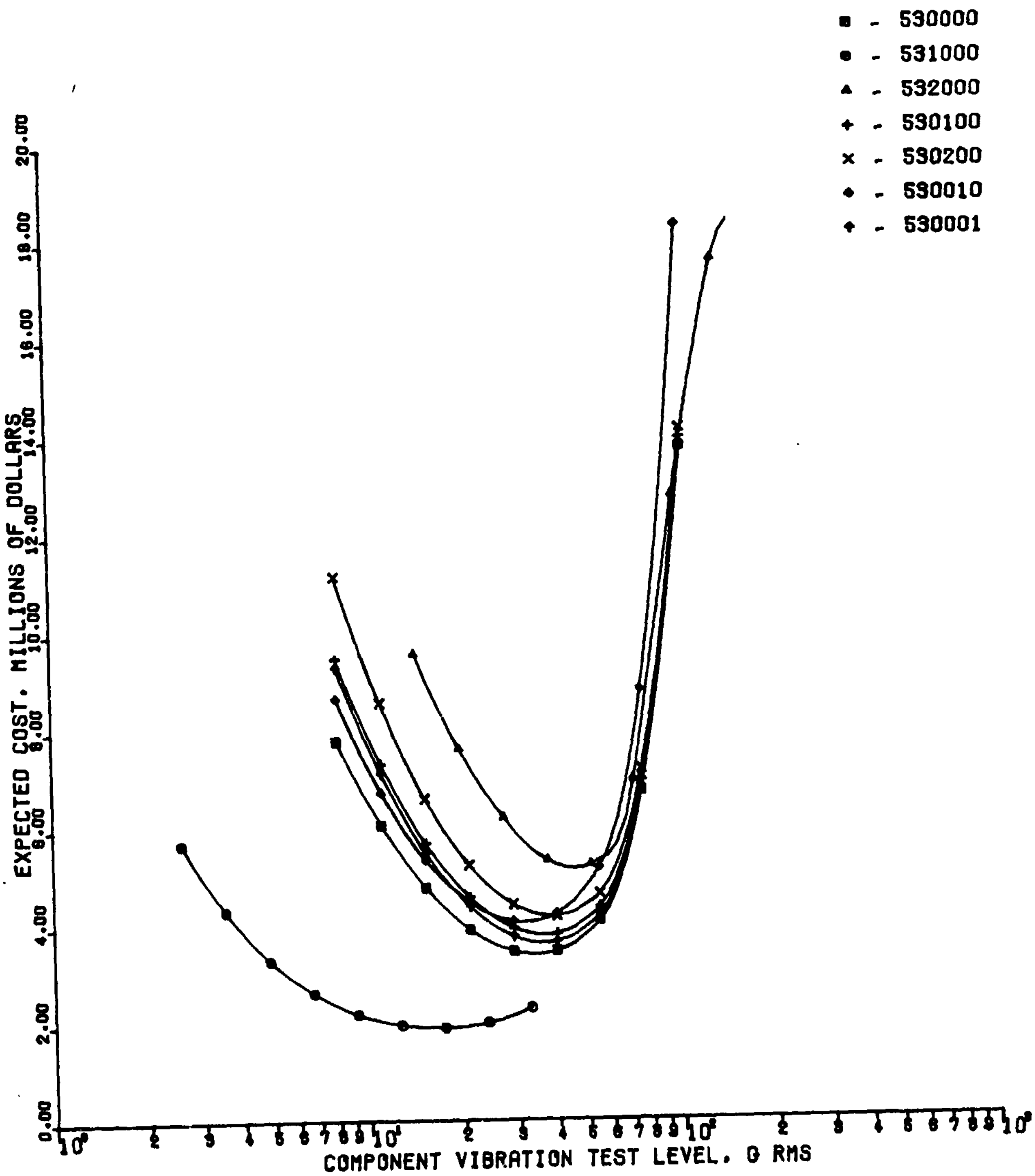

Figure 4-19 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 7B, Payload 7,2

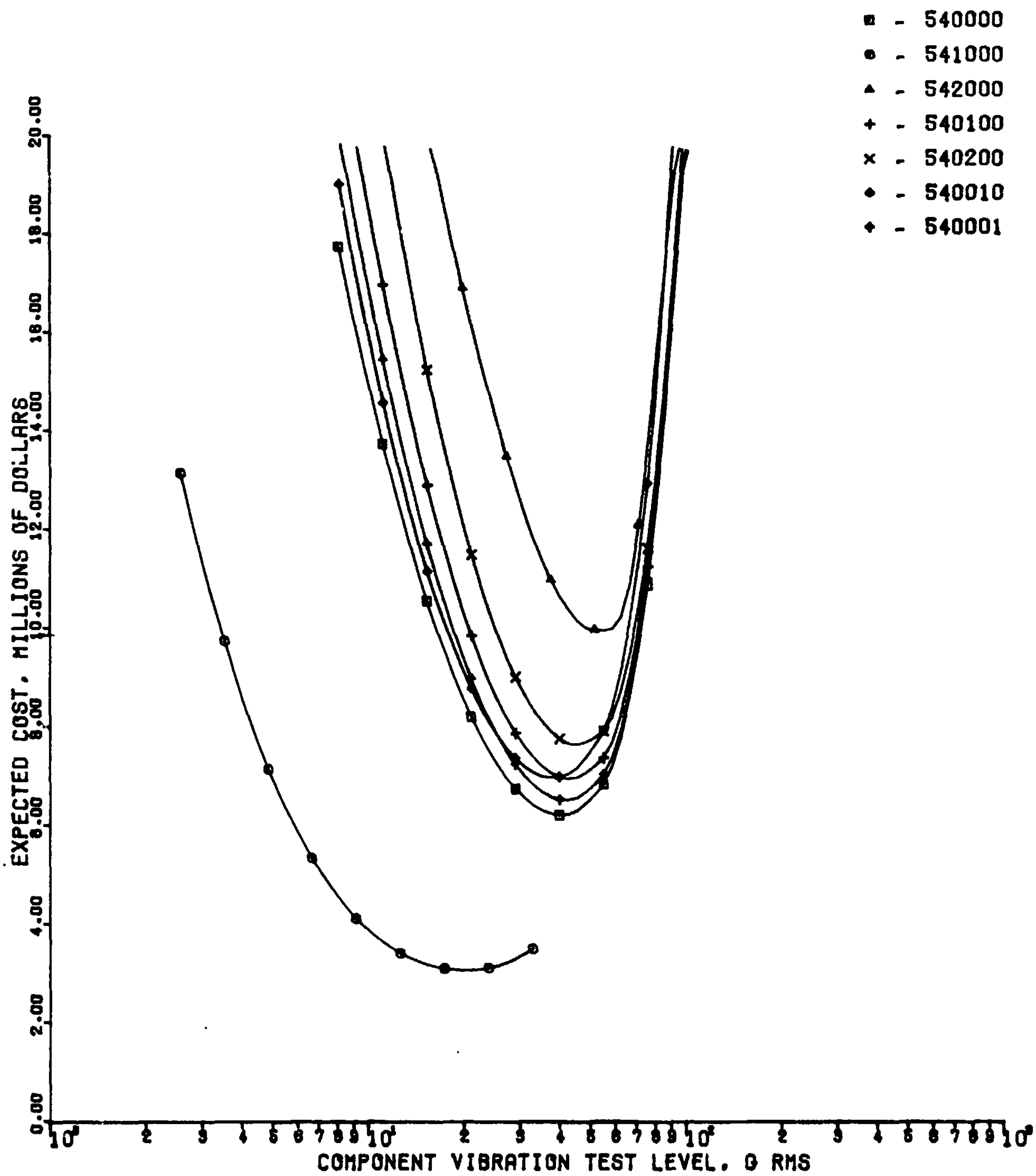

Figure 4-20 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 7B, Payload 7,6

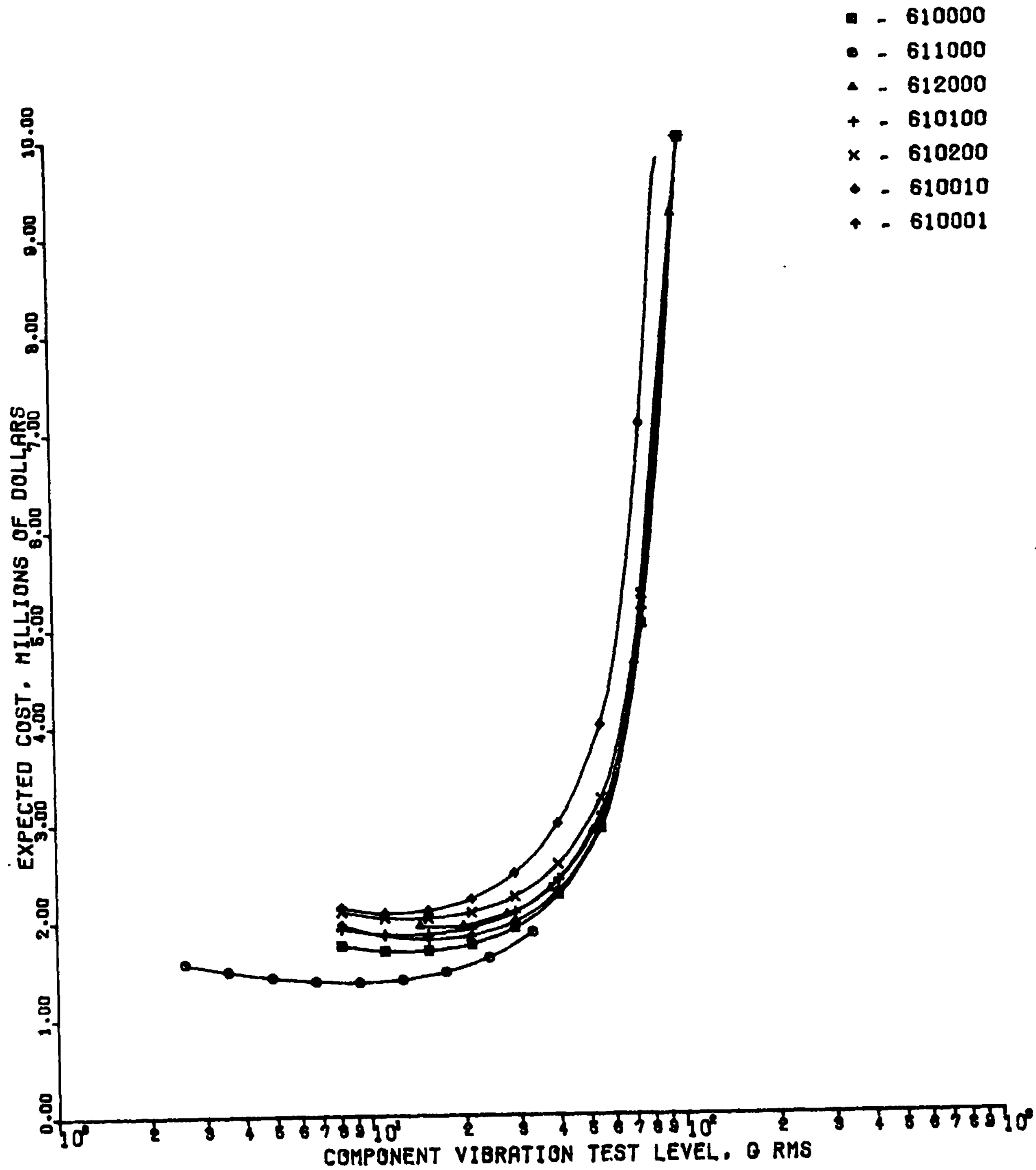

Figure 4-21 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 8, Payload 1,2

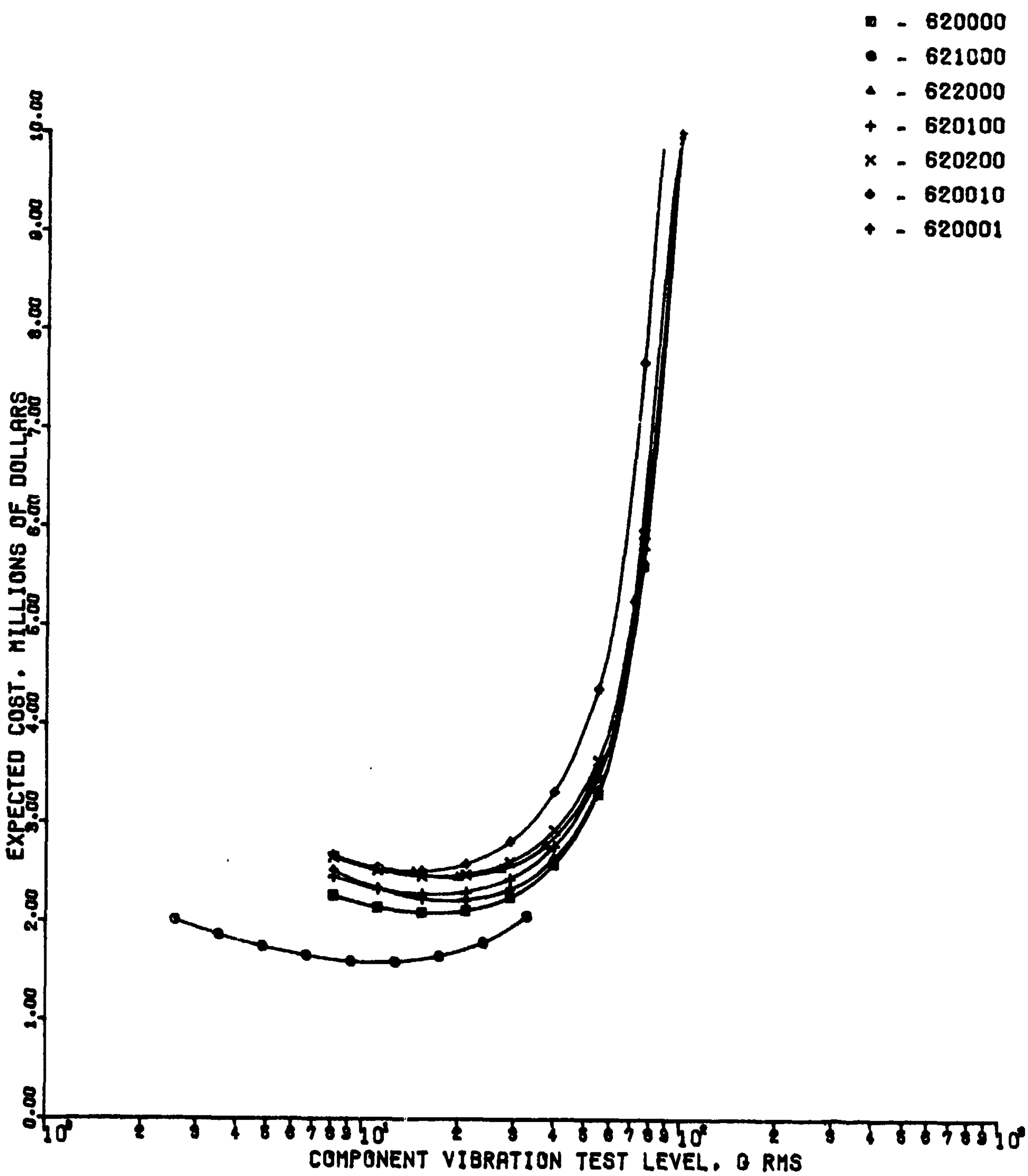

Figure 4-22 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 8, Payload 1,6

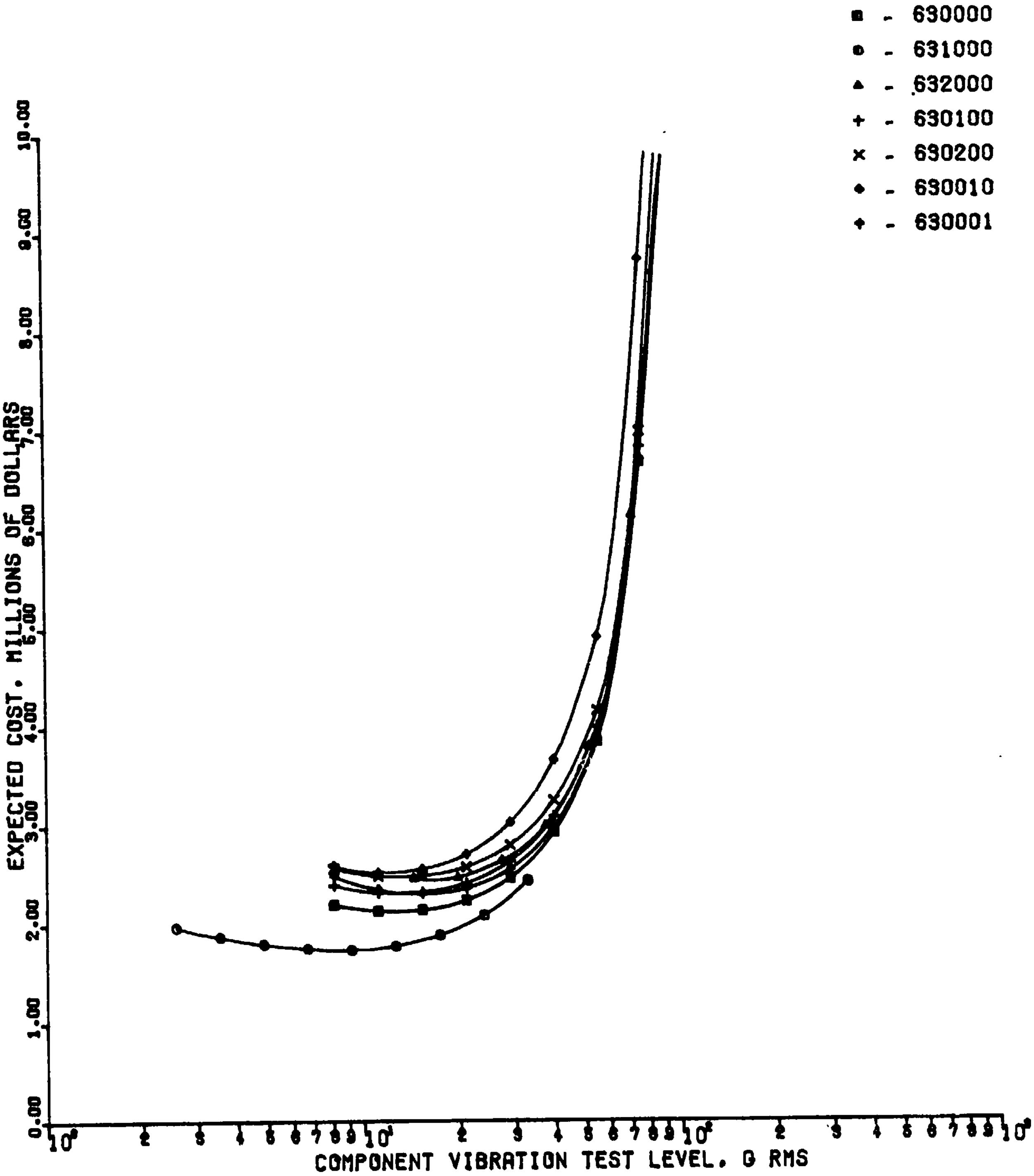

Figure 4-23 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 8, Payload 7,2

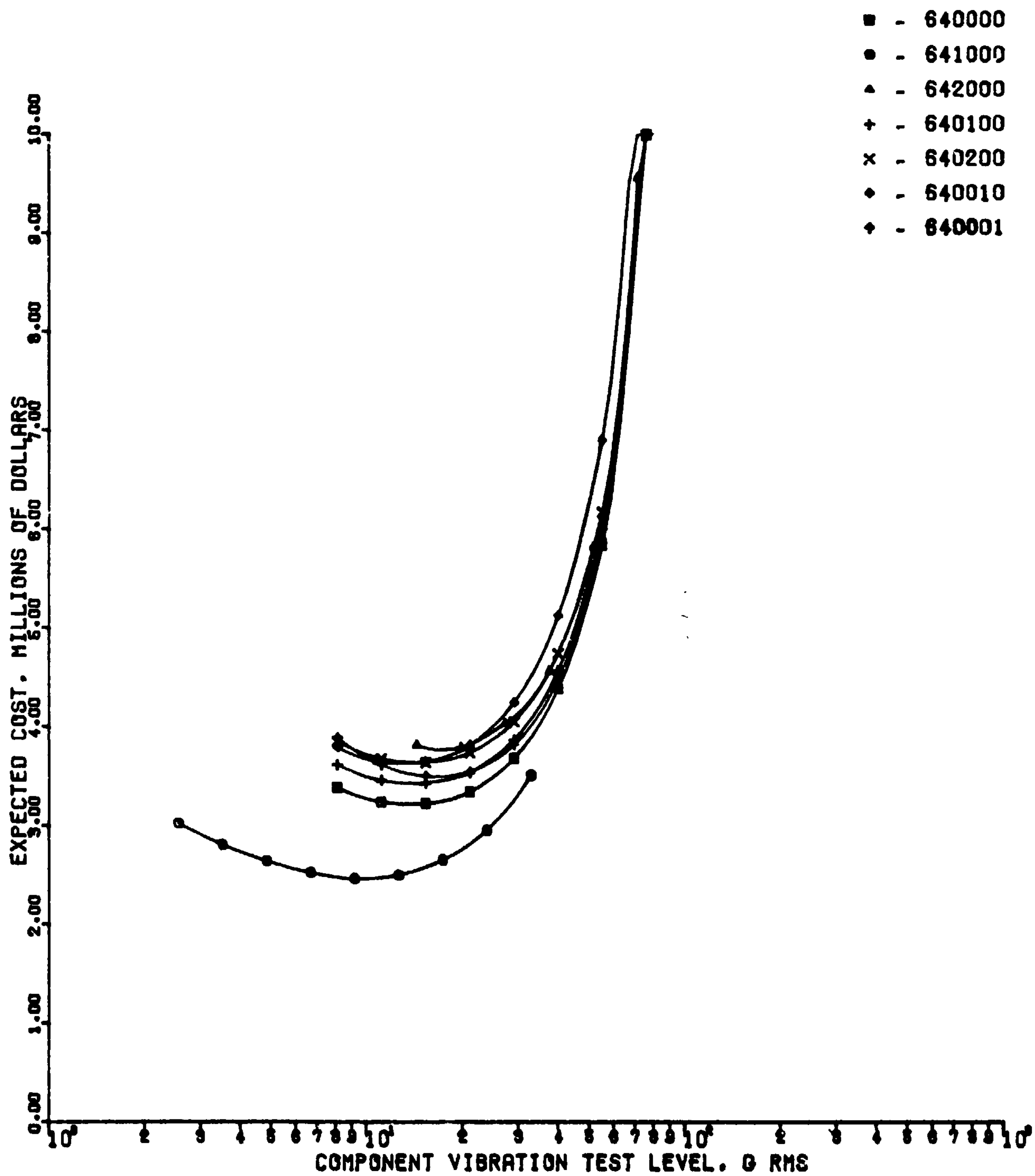

Figure 4-24 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 8, Payload 7,6

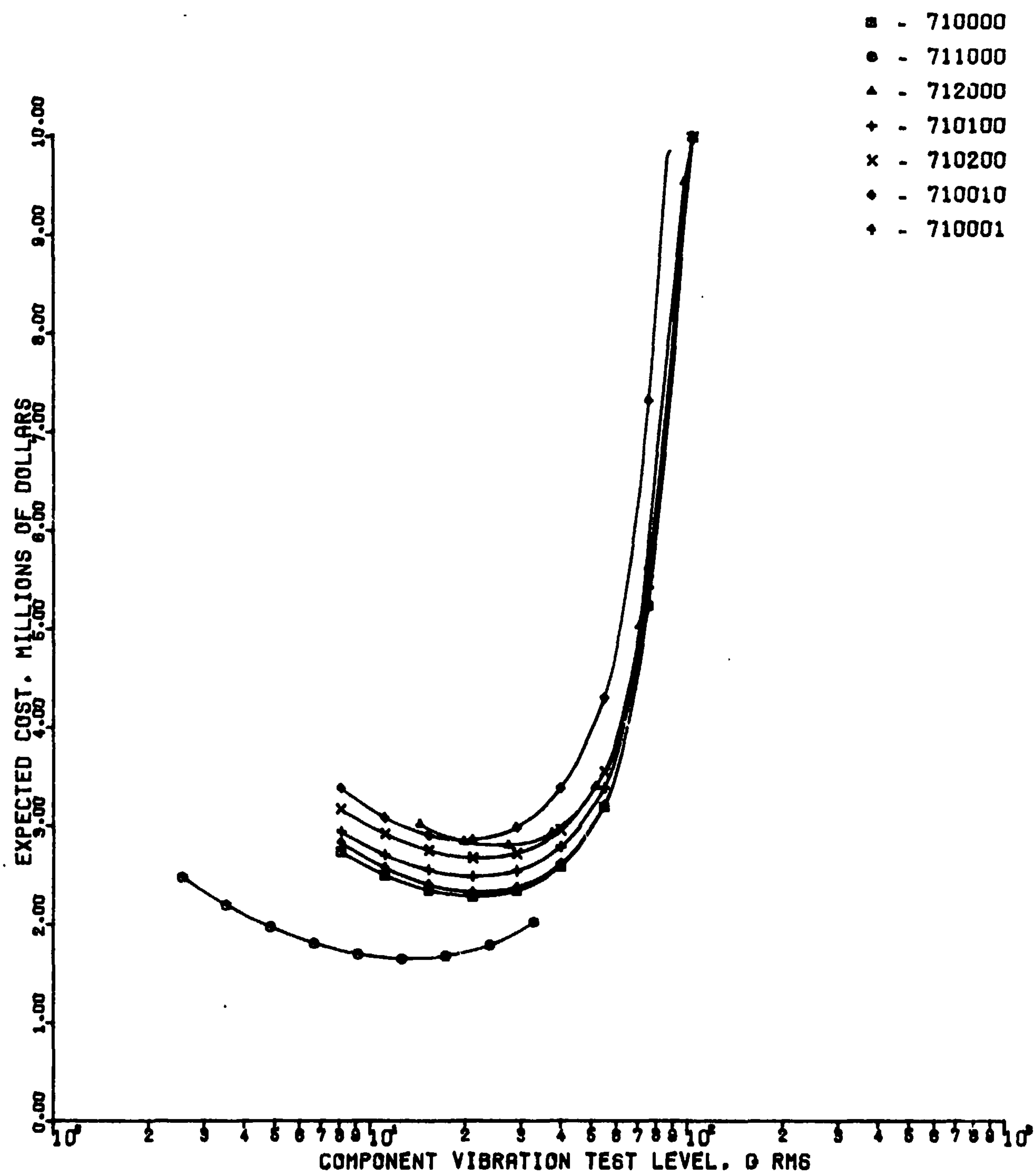

Figure 4-25 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 9, Payload 1,2

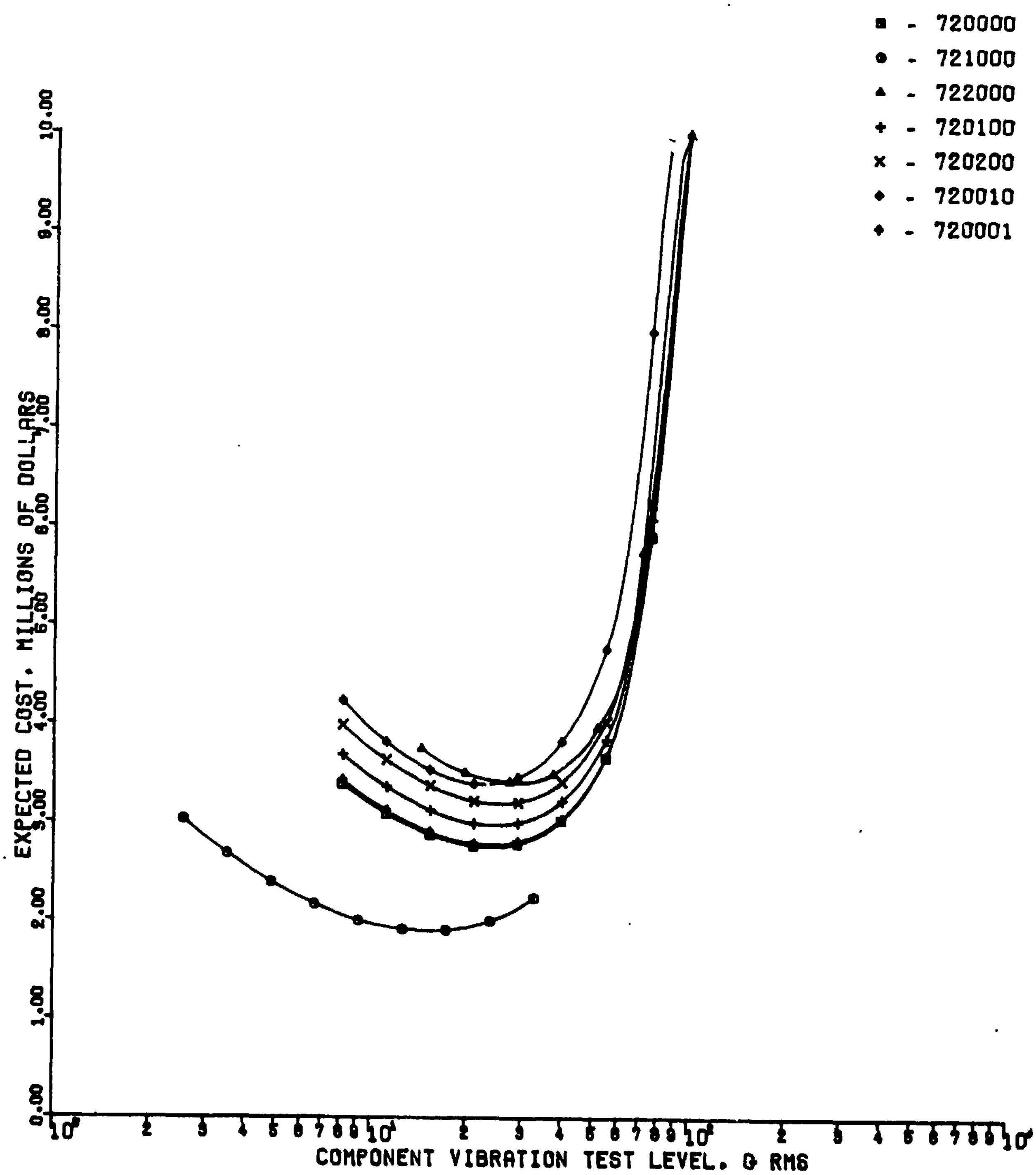

Figure 4-26 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 9, Payload 1,6

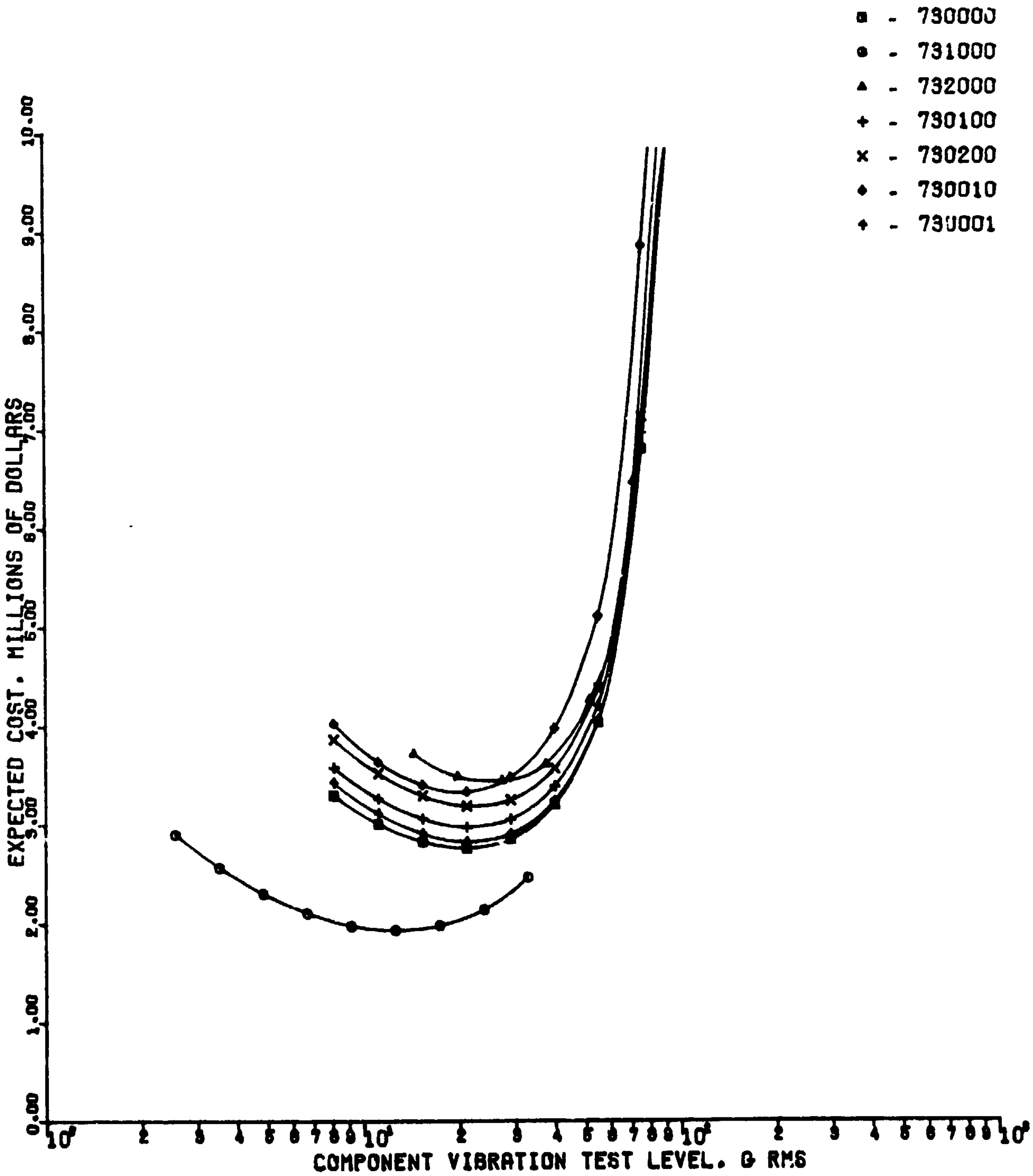

Figure 4-27 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 9, Payload 7,2

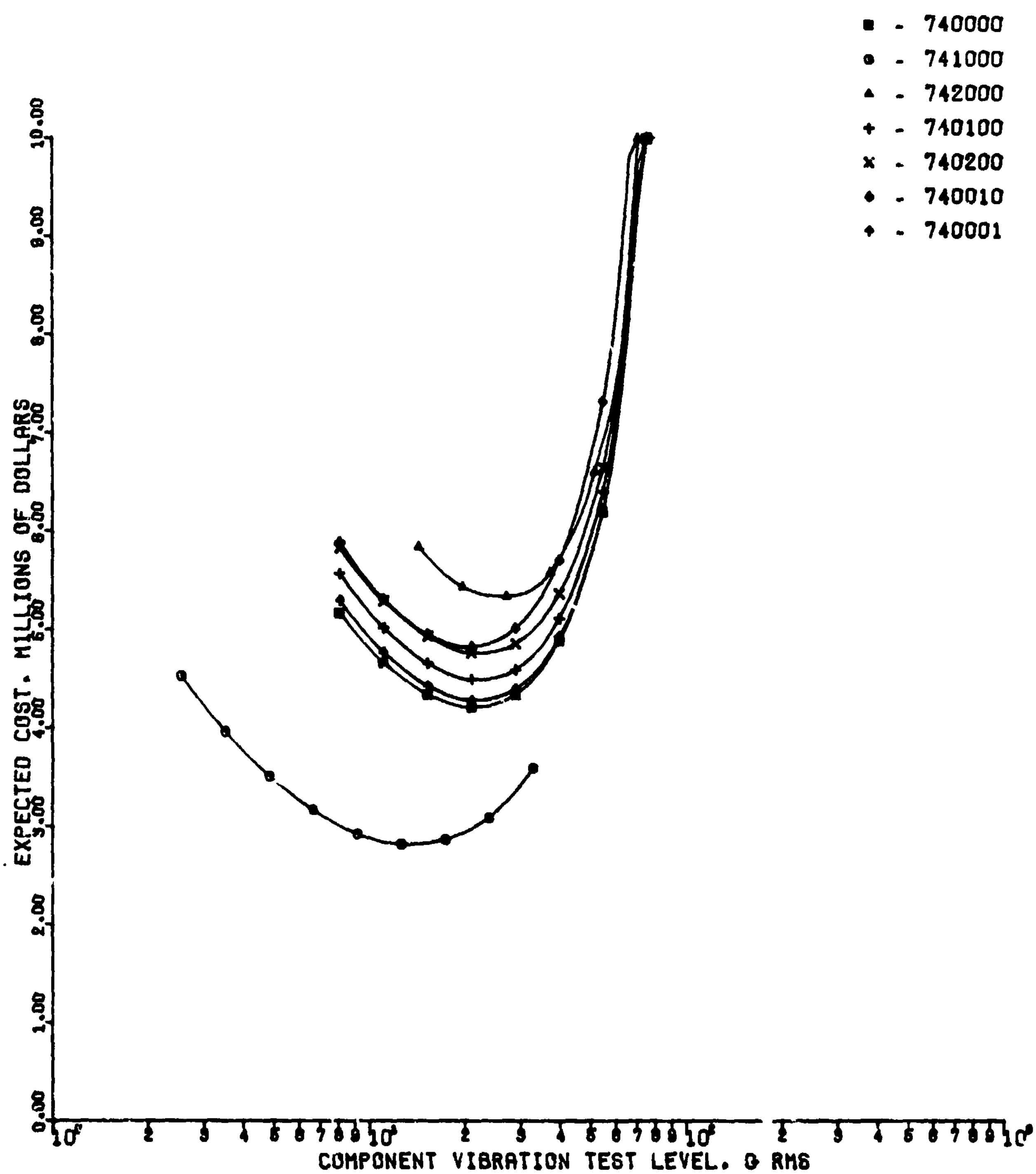

Figure 4-28 Costs for Optimum Assembly Acoustic Test Levels
Test Plan 9, Payload 7,6

test plans. In Phase B optimum vibration levels were not attainable for Test Plans 4 and 5 and "optimum" data given for these test plans was for a representative component design strength associated with a component vibration test level of approximately 13 g rms.

4.2 REVISED BASELINE

For Phase B the emphasis was placed on the development of the methodology and a set of values was selected for the parameters. An extensive pictorial presentation of data was given in Section 6 of Reference 2. Graphs of costs, cost elements, and flight failure probability were shown for the evaluation of the 7 vibroacoustic test plans of Phase B for the 4 payload configurations considered. The optimum results were summarized by test plan and payload in Tables 6-1 and 6-2, respectively, of Reference 2. Since several modifications have been made to the decision models used to evaluate the test plans, it is deemed necessary to present here a discussion of the revised baseline data. An extensive pictorial presentation is not made here for the revised baseline. The TECF and FFP data are given in the Addendum and the TECF data for the assembly test level at which the optimum cost occurs are shown in Figures 4-1 to 4-28. The case code for the baseline data is XY0000, where X is the test plan ID and Y is the payload ID defined in Section 3.1. On the figures the symbol for the baseline data is ◘ . A summary of the revised baseline optimum data by payload is given in Table 4-8. Also given is the cost rank and the reliability rank.

A comparison of the expected costs given in Table 4-8 indicates that Test Plans 4, 5 and 8 are the most attractive. Minimum cost (rank = 1) is achieved with Test Plan 4, which involves subassembly testing only, for all of the payload configurations considered. Test Plan 5, which involves system testing only, ranks second, followed

Table 4-8

Summary of Optimums By Payloads
Variation 0000
Phase C Baseline

Payload	Test Plan	Expected Cost ($ x 10^6)	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Associated Vibroacoustic Reliability	Cost Rank	Reliability Rank
1,2	4	0.988	19.767	151	0.99790	1	2
	5	1.469	30.910	147	0.99629	2	3
	6	3.050	54.917	-	0.98018	6	7
	7	3.655	37.437	-	0.98279	7	6
	7B	2.859	37.437	-	0.98351	5	5
	8	1.683	12.642	153	0.99840	3	1
	9	2.279	21.071	147	0.99541	[illegible]	4
1,6	4	1.263	25.521	153	0.99666	1	1
	5	1.818	35.121	149	0.99330	2	4
	6	4.894	58.539	-	0.94885	6	7
	7	5.148	48.333	-	0.96737	7	6
	7B	4.339	48.333	-	0.96808	5	5
	8	2.090	16.321	153	0.99591	3	2
	9	2.751	23.942	151	0.99490	4	3
7,2	4	1.199	19.767	151	0.98552	1	1
	5	1.668	30.910	145	0.96337	2	4
	6	3.308	45.342	-	0.85499	5	7
	7	4.182	35.121	-	0.[illegible]8493	7	6
	7B	3.[illegible]5	35.121	-	0.88557	6	5
	8	2.1[illegible]	12.642	151	0.98173	3	2
	9	2.764	21.071	147	0.96877	4	3
7,6	4	1.677	21.071	153	0.97427	1	1
	5	2.449	30.910	149	0.95009	2	3
	6	5.808	54.9[illegible]	-	0.63366	5	7
	7	7.[illegible]20	39.906	-	0.74027	7	6
	7B	6.204	39.906	-	0.74081	6	5
	8	3.2[illegible]4	13.475	153	0.96836	3	2
	9	4.211	21.071	149	0.94010	4	4

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by Test Plan 8, which involves component and subassembly testing, and Test Plan 9, which involves component and system testing. Test Plan 7, which involves component testing only, ranks last. The rankings of Test Plans 6 and 7 vary with the payload. For Payloads 1,2 and 1,6 Test Plan 7B ranks fifth and Test Plan 6 ranks sixth; these rankings are reversed for the other two payloads.

The optimum component vibration test/design level varies from 20 to 26 g rms for Test Plan 4, from 31 to 35 g rms for Test Plan 5, from 45 to 59 g rms for Test Plan 6, from 35 to 48 g rms for Test Plans 7 and 7B, from 13 to 16 g rms for Test Plan 8, and from 21 to 24 g rms for Test Plan 9. The lowest component vibration levels are obtained for Test Plan 8, followed by Test Plan 4 or 9, Test Plan 5, Test Plans 7 and 7B, and Test Plan 6, which has the highest component vibration levels.

The optimum assembly acoustic test level varies from 151 to 153 dB for Test Plans 4 and 8, from 145 to 149 dB for Test Plan 5, and from 147 to 151 dB for Test Plan 9. The lowest assembly acoustic test levels are obtained for those test plans that utilize system testing, Test Plans 5 and 9, and the highest assembly test levels are obtained for those test plans that utilize subassembly testing, Test Plans 4 and 8.

The payload flight vibroacoustic reliability associated with the optimum cost is also given in Table 4-8 for the revised baseline. In this study, the flight vibroacoustic reliability is defined as the probability of no data loss from the payload as a result of a vibration failure of a component. For all payload configurations the test plans that utilize subassembly testing, Test Plans 4 and 8, rank 1, 2. The test plans that utilize system testing, Test Plans 5 and 9, rank 3, 4. Test Plans 7B, 7, and 6 rank 5, 6, and 7, respectively.

For all payload configurations a cost saving of $800,000 is achieved when protoflight structural testing, Test Plan 7B, is used instead of no structural testing, Test Plan 7.

A comparison of the test plan cost rankings of the baseline for Phases B and C is given in Table 4-9. In both phases subassembly only testing ranks first, system only testing ranks second, component and subassembly testing ranks third, component and system testing ranks fourth, and component only testing ranks last. For Phase B component, system and SDM testing ranks fifth and component and SDM testing ranks sixth. For Phase C either no testing or component with protoflight structure testing ranks fifth or sixth.

A comparison of Table 4-8 with Table 6-2 of Reference 2 shows that, for comparable test plans, the optimum costs for Phase C are less than the optimum costs for Phase B and, in general, the associated test levels of Phase C are lower than those of Phase B. The main reason for the lower costs is the deletion of the direct cost of procuring prototype components for the vibration testing at the component level of assembly in Test Plans 1, 1A, 2, 3, and 3A of Phase B from the comparable test plans of Phase C. The component vibration test levels for Test Plans 4 and 5 of Phase C are higher than those of Phase B. The reason for this is that true optimum vibration test levels are obtained for Phase C, whereas for Phase B no true optimums were attainable and values were given for vibration test levels associated with a representative component design strength.

The effects of variations in four key parameters are discussed in Section 4.3. That discussion compares the data for each variation with the baseline data discussed in this section.

Table 4-9

Comparison of Cost Ranking for Phase B and Phase C Baseline

Test Plan	Cost Rank	
	Phase B	Phase C
1	7	-
1A	6	-
2	3	-
3	4	-
3A	5	-
4	1	1
5	2	2
6	-	5 or 6
7	-	7
7B	-	5 or 6
8	-	
9	-	4

4.3 PARAMETER VARIATIONS

A parameter study was performed to determine the effects of key parameter variations on the evaluation of the seven vibroacoustic test plans. This section discusses the results obtained for varying the following key parameters:

1. Shuttle payload bay internal acoustic environment
2. STS Launch cost
3. Degree of redundancy in the housekeeping section
4. Component retest/repair cost

The effects of these parameter variations on the cost ranking, optimum expected costs, optimum component vibration test/design levels, optimum assembly acoustic test levels, and vibroacoustic reliability ranking are discussed.

4.3.1 SHUTTLE PAYLOAD BAY INTERNAL ACOUSTIC ENVIRONMENT

Two variations of the shuttle payload bay internal acoustic environment were considered. The first variation was 135 dB, which is 10 dB below the baseline value of 145 dB; the second variation, 150 dB, is 5 dB above the baseline value. The third digit of the six-digit case code identifies the shuttle payload bay internal acoustic environment. The case codes for the data of these variations are XY1000 and XY2000 for the 135 dB and 150 dB environments, respectively, where X is the test plan ID and Y is the payload ID defined in Sections 3.1. The TECF and FFP data are given in the Addendum and the TECF data for the assembly test level at which the optimum cost occurs are shown in Figures 4-1 to 4-28. On the figures the symbols for these variations are ⊙ and ▲ for the 135 dB and 150 dB environments, respectively. The environment is included in the title of the TECF and FFP data. Summaries of the optimum data by payload are given in Tables 4-10 and 4-11 for the 135 dB and 150 dB environments, respectively.

A comparison of Tables 4-10 and 4-11 with Table 4-8 shows that variations in the environment have the most significant effect on the cost rankings. For the 135 dB environment there are two rank changes for Payloads 1,2 and 1,6 and three rank changes for Payloads 7,2 and 7,6. For Payload 1,2 the rankings of Test Plans 7B and 9 are affected; for Payload 1,6, Test Plans 6 and 7B; for Payload 7,2, Test Plans 6, 7B, and 9; for Payload 7,6, Test Plans 6, 8 and 9. For the 150 dB environment there are two rank changes for Payloads 1,2, 1,6, and 7,2 and three rank changes for Payload 7,6. For Payload 1,2 the rankings of Test Plans 5 and 8 are affected; for Payload 1,6, Test Plans 6 and 7; for Payload 7,2, Test Plans 6 and 7B; for Payload 7,6, Test Plans 6, 7, and 7B. For the 135 dB environment Test Plan 4 ranks first for all payloads, Test Plan 5 ranks second for all payloads, and Test Plan 7 ranks last for all payloads. For the 150 dB environment Test Plan 4 ranks first for all payloads, Test Plan 7B ranks fifth for all payloads, and Test Plan 9 ranks fourth for all payloads.

The optimum expected costs for the 135 dB environment are lower than the baseline costs in all cases. The amount of the decrease varies with payload and test plan from $0.256M for Payload 1,2 with Test Plan 4 to $3.547M for Payload 7,6 with Test Plan 6. In all cases the smallest decrease is obtained for Test Plan 4, followed by Test Plans 8, 5, 9, 7B, 7, and 6, which has the largest decrease.

The optimum expected costs for the 150 dB environment are higher than the baseline costs in all cases. The amount of the increase varies with payload and test plan from $0.220M for Payload 1,2 with Test Plan 4 to $5.274M for Payload 7,6 with Test

Table 4-10

Summary of Optimums By Payload
Variation 1000
Phase C 135 DB Environment

Payload	Test Plan	Expected Cost ($ x 10^6)	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Associated Vibroacoustic Reliability	Cost Rank	Reliability Rank
1,2	4	0.732	12.619	141	0.99918	1	1
	5	0.943	18.512	135	0.99851	2	3
	6	1.680	27.155	-	0.99571	6	5
	7	2.390	18.512	-	0.99473	7	7
	7B	1.602	18.512	-	0.99545	4	6
	8	1.366	9.170	141	0.99891	3	2
	9	1.647	13.451	135	0.99780	5	4
1,6	4	0.840	16.292	143	0.99867	1	1
	5	1.076	22.421	137	0.99726	2	3
	6	2.008	32.890	-	0.99123	5	5
	7	2.854	23.899	-	0.99050	7	7
	7B	2.063	23.899	-	0.99122	6	6
	8	1.584	11.106	143	0.99820	3	2
	9	1.900	15.284	139	0.99708	4	4
7,2	4	0.882	12.619	141	0.99430	1	1
	5	0.988	18.512	133	0.98699	2	3
	6	1.743	25.475	-	0.97248	4	5
	7	2.686	16.292	-	0.96141	7	7
	7B	1.898	16.292	-	0.96211	5	6
	8	1.735	8.603	141	0.99202	3	2
	9	1.934	12.619	135	0.98365	6	4
7,6	4	1.052	13.451	141	0.98392	1	1
	5	1.257	19.732	135	0.97153	2	3
	6	2.261	28.946	-	0.93407	3	5
	7	3.848	19.732	-	0.91813	7	7
	7B	3.055	19.732	-	0.91880	6	6
	8	2.459	9.775	141	0.97876	4	2
	9	2.812	13.451	137	0.96728	5	4

Table 4-11

Summary of Optimums By Payload
Variation 2000
Phase C 150 DB Environment

Payload	Test Plan	Expected Cost ($ x 10^6)	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Associated Vibroacoustic Reliability	Cost Rank	Reliability Rank
1,2	4	1.208	23.963	158	0.99815	1	1
	5	1.947	35.152	154	0.99585	3	3
	6	5.064	62.455	-	0.94541	6	7
	7	5.151	48.375	-	0.96439	7	6
	7B	4.343	48.375	-	0.96509	5	5
	8	1.923	17.413	158	0.99797	2	2
	9	2.802	25.543	154	0.99548	4	4
1,6	4	1.605	30.937	158	0.99511	1	2
	5	2.438	37.470	156	0.99264	2	3
	6	9.582	66.573	-	0.86816	7	7
	7	7.926	62.455	-	0.93328	6	6
	7B	7.092	62.455	-	0.93396	5	5
	8	2.450	18.561	160	0.99659	3	1
	9	3.403	29.023	156	0.99244	4	4
7,2	4	1.476	22.480	156	0.97805	1	1
	5	2.284	35.152	152	0.95579	2	3
	6	5.546	58.591	-	0.69986	6	7
	7	5.939	45.383	-	0.78145	7	6
	7B	5.129	45.383	-	0.78202	5	5
	8	2.442	16.335	156	0.97554	3	2
	9	3.443	25.543	152	0.95133	4	4
7,6	4	2.186	2[illegible].543	158	0.96331	1	1
	5	3.465	35.152	154	0.91769	2	3
	6	11.082	62.455	-	0.37068	7	7
	7	10.782	54.966	-	0.57111	6	6
	7B	9.938	54.966	-	0.57152	5	5
	8	3.762	17.413	158	0.95858	3	2
	9	5.336	27.228	154	0.91425	4	4

Plan 6. In all cases the smallest increase is obtained for Test Plan 4, followed by Test Plans 8, 5, 9, 7B, 7, and 6, which has the largest increase.

The optimum component vibration levels for the 135 dB environment are lower than the baseline vibration levels in all cases. The amount of the decrease varies with the payload and test plan from 3.472 g rms for Payload 1,2 with Test Plan 8 to 27.762 g rms for Payload 1,2 with Test Plan 6. Except for Payload 1,6, the smallest decrease is obtained for Test Plan 8, followed by Test Plans 4, 9, 5, 7, 7B, and 6, which has the largest decrease. For Payload 1,6 the amount of the decreases for Test Plans 4 and 9 is reversed.

The optimum component vibration levels for the 150 dB environment are higher than the baseline vibration levels in all cases. The amount of the increase varies with payload and test plan from 2.240 g rms for Payload 1,6 with Test Plan 8 to 15.060 g rms for Payload 7,6 with Test Plans 7 and 7B. No particular pattern is evident. For each payload the four smallest increases are obtained from Test Plans 4, 5, 8, and 9 and the three largest increases are obtained from Test Plans 6, 7, and 7B.

The optimum assem acoustic test levels for the 135 dB environment are lower than the baseline acou levels in all cases. The amount of the decrease varies with the payload and test plan from 10 dB for Payload 1,2 with Test Plan 4 to 14 dB for Payload 7,6 with Test Plan 5. In all cases the smallest decrease is obtained for Test Plan 4, followed by Test Plans 8, 9, and 5, which has the largest decrease.

The optimum assembly acoustic test levels for the 150 dB environment are higher than the baseline acoustic levels in all cases. The amount of the increase varies with payload and test plan and is either 5 or 7 dB.

A comparison of Tables 4-10 and 4-11 with Table 4-8 shows that variations in the environment also have the most significant effect on the reliability rankings. For the 135 dB environment there are five rank changes for Payloads 1,2, 1,6, and 7,2 and three rank changes for Payload 7,6. For Payload 1,2 the rankings of Test Plans 4, 6, 7, 7B, and 8 are affected; for Payloads 1,6 and 7,2, Test Plans 5, 6, 7, 7B, and 9; for Payload 7,6, Test Plans 6, 7, and 7B. For the 150 dB environment there are two rank changes for Payloads 1,2 and 7,2, four rank changes for Payload 1,6, and no rank changes for Payload 7,6. For Payload 1,2 the rankings of Test Plans 4 and 8 are affected; for Payload 1,6, Test Plans 4, 5, 8, and 9; for Payload 7,2, Test Plans 5 and 9. For the 135 dB environment Test Plan 4 ranks first for all payloads, followed by Test Plans 8, 5, 9, 6, 7B, and 7, which has the lowest vibroacoustic reliability. Except for Payload 1,6, for the 150 dB environment Test Plan 4 ranks first, followed by Test Plans 8, 5, 9, 7B, 7, and 6, which has the lowest vibroacoustic reliability. For Payload 1,6 the rankings of Test Plans 4 and 8 are reversed.

4.3.2 STS LAUNCH COST

Two variations of the STS launch cost were considered. The first variation was \$17.5M, which is \$4.0M above the baseline value of \$13.5M; the second variation, \$21.5M, is \$8.0M above the baseline value. The fourth digit of the six-digit case code identifies the STS launch cost. The case codes for the data of these variations are XY0100 and XY0200 for the \$17.5M and \$21.5M STS launch costs, respectively, where X is the test plan ID and Y is the payload ID defined in Section 3.1. The TECF and FFP data are given in the Addendum and the TECF data for the assembly test level at which the optimum cost occurs are shown in Figures 4-1 to 4-28. On the figures the symbols for these variations are + and x for the \$17.5M and \$21.5M STS launch costs, respectively.

Summaries of the optimum data by payload are given in Tables 4-12 and 4-13 for the $17.5M and $21.5M STS launch costs, respectively.

A comparison of Tables 4-12 and 4-13 with Table 4-8 shows the effect of these variations on the cost rankings. For both STS launch costs there are no rank changes for Payload 1,2 and two rank changes for Payloads 1,6, 7,2, and 7,6. For Payload 1,6 the rankings of Test Plans 6 and 7 are affected; for Payloads 7,2 and 7,6, Test Plans 6 and 7B. Except for Payload 1,6, Test Plan 4 ranks first, followed by Test Plans 5, 8, 9, 7B, 6, and 7, which has the highest optimum cost. For Payload 1,6 the rankings of Test Plans 6 and 7 are reversed.

The optimum expected costs for the two STS launch cost variations are higher than the baseline costs in all cases. The amount of the increase varies with payload and test plan. For the $17.5M STS launch cost the increase varies from $0.166M for Payload 1,2 with Test Plan 4 to $1.193M for Payload 7,6 with Test Plan 6. For the $21.5M STS launch cost the increase varies from $0.328M for Payload 1,2 with Test Plan 4 to $2.343M for Payload 7,6 with Test Plan 6.

The optimum component vibration levels for the two STS launch cost variations are the same or higher than the baseline vibration levels in all cases. The amount of the increase varies with payload and test plan from 0 g rms to 9.575 g rms. No change in the vibration level occurs 15 times. For both variations the maximum change of 9.575 g rms occurs for Payload 7,2 with Test Plan 6.

The optimum assembly acoustic test levels for the two launch cost variations are the same or higher than the baseline acoustic levels in all cases. The amount of the increase varies with payload and test plan and is either 0 or 2 dB.

Table 4-12

Summary of Optimums By Payload
Variation 0100
Phase C STS Launch Cost = $17.5M

Payload	Test Plan	Expected Cost ($ x 10^6)	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Associated Vibroacoustic Reliability	Cost Rank	Reliability Rank
1,2	4	1.154	21.071	153	0.99875	1	1
	5	1.666	32.948	147	0.99646	2	4
	6	3.710	64.917	-	0.98018	6	7
	7	4.269	39.906	-	0.98436	7	6
	7B	3.229	39.906	-	0.98507	5	5
	8	1.850	13.475	153	0.99846	3	2
	9	2.484	21.071	149	0.99703	4	3
1,6	4	1.454	25.521	155	0.99794	1	1
	5	2.031	35.121	151	0.99562	2	3
	6	6.038	58.539	-	0.94885	7	7
	7	5.989	51.520	-	0.97039	6	6
	7B	4.934	51.520	-	0.97109	5	5
	8	2.279	17.397	155	0.99762	3	2
	9	2.971	25.521	151	0.99514	4	4
7,2	4	1.374	19.767	151	0.98552	1	1
	5	1.875	30.910	147	0.97466	2	3
	6	4.000	54.917	-	0.87978	6	7
	7	4.828	37.437	-	0.89468	7	6
	7B	3.786	37.437	-	0.89533	5	5
	8	2.313	12.642	151	0.98173	3	2
	9	2.976	21.071	147	0.96877	4	4
7,6	4	1.677	21.071	153	0.97427	1	1
	5	2.701	32.948	149	0.95216	2	3
	6	7.001	54.917	-	0.68366	6	7
	7	6.001	42.537	-	0.76080	7	6
	7B	6.936	42.537	-	0.76135	5	5
	8	3.427	14.364	153	0.96951	3	2
	9	4.486	22.461	149	0.94296	4	4

Table 4-13

Summary of Optimums By Payload
Variation 0200
Phase C STS Launch Cost = $21.5M

Payload	Test Plan	Expected Cost ($ x 10^6)	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Associated Vibroacoustic Reliability	Cost Rank	Reliability Rank
1,2	4	1.316	21.071	153	0.99875	1	1
	5	1.853	32.948	149	0.99764	2	3
	6	4.369	54.917	-	0.98018	6	7
	7	4.860	42.537	-	0.98576	7	6
	7B	3.575	42.537	-	0.98648	5	5
	8	2.016	13.475	153	0.99846	3	2
	9	2.671	22.461	149	0.99717	4	4
1,6	4	1.628	27.204	155	0.99801	1	1
	5	2.240	35.121	151	0.99562	2	3
	6	7.139	62.399	-	0.95199	7	7
	7	6.775	54.917	-	0.97311	6	6
	7B	5.474	54.917	-	0.97382	5	5
	8	2.459	17.397	155	0.99762	3	2
	9	3.187	25.521	151	0.99514	4	4
7,2	4	1.540	19.767	153	0.99103	1	1
	5	2.073	32.948	147	0.97581	2	3
	6	4.659	54.917	-	0.87978	6	7
	7	5.450	39.906	-	0.90374	7	6
	7B	4.163	39.906	-	0.90440	5	5
	8	2.480	12.642	153	0.98893	3	2
	9	3.186	22.461	147	0.97042	4	4
	4	2.075	22.461	153	0.97516	1	1
	5	2.950	32.948	149	0.95216	2	4
	6	8.151	58.539	-	0.70027	6	7
	7	8.934	45.342	-	0.78019	7	6
	7B	7.622	45.342	-	0.78075	5	5
	8	3.637	14.364	153	0.96951	3	2
	9	4.755	22.461	151	0.96328	4	3

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A comparison of Tables 4-12 and 4-13 with Table 4-8 shows the effect of the STS launch cost variations on the reliability rankings. For the $17.5M STS launch cost there are four rank changes for Payload 1,2, two rank changes for Payloads 1,6 and 7,2, and no rank changes for Payload 7,6. For Payload 1,6 the rankings of Test Plans 4, 5, 8, and 9 are affected; for Payloads 1,6 and 7,2, Test Plans 5 and 9. For the $21.5M STS launch cost there are two rank changes for each payload. For Payload 1,2 the rankings of Test Plans 4 and 8 are affected; for the other payloads, Test Plans 5 and 9. Except for Payload 1,2, for the $17.5M STS launch cost Test Plan 4 ranks first, followed by Test Plans 8, 5, 9, 7B, 7, and 6, which has the lowest vibroacoustic reliability. For Payload 1,2 the rankings of Test Plans 5 and 9 are reversed. Except for Payload 7,6, for the $21.5M STS launch cost Test Plan 4 ranks first, followed by Test Plans 8, 5, 9, 7B, 7 and 6. For Payload 7,6 the rankings of Test Plans 5 and 9 are reversed.

4.3.3 DEGREE OF REDUNDANCY

Only one variation of the degree of redundancy in the housekeeping section of the payload was considered. This variation was double redundancy instead of the single redundancy of the baseline. The fifth digit of the six-digit case code identifies the degree of redundancy. The case code for the data of this variation is XY0010, where X is the test plan ID and Y is the payload ID defined in Section 3.1. The TECF and FFP data are given in the Addendum and the TECF data for the assembly test level at which the optimum cost occurs are shown in Figures 4-1 to 4-28. On the figures the symbol for this variation is ◇ . A summary of the optimum data by payload is given in Table 4-14.

Table 4-14

Summary of Optimums By Payload
Variation 0010
Phase C Double Redundancy

Payload	Test Plan	Expected Cost ($ x 10^6)	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Associated Vibroacoustic Reliability	Cost Rank	Reliability Rank
1,2	4	[illegible].078	18.544	151	0.99784	1	1
	5	1.689	28.997	147	0.99617	2	3
	6	3.375	45.342	-	0.97750	5	7
	7	4.345	32.948	-	0.98060	7	6
	7B	3.547	32.546	-	0.98132	6	5
	8	2.076	11.860	151	0.99726	3	2
	9	2.852	19.767	147	0.99524	4	4
1,6	4	[illegible]	22.461	153	0.99641	1	1
	5	2.077	32.948	149	0.99302	2	3
	6	5.[illegible]24	58.539	-	0.94992	6	7
	7	6.015	42.537	-	0.96120	7	6
	7B	5.201	42.537	-	0.96190	5	5
	8	2.515	14.364	153	0.99559	3	2
	9	3.387	22.461	149	0.99165	4	4
7,2	4	1.287	18.544	151	0.98497	1	1
	5	1.871	28.997	145	0.96159	2	3
	6	[illegible]	45.342	-	0.85661	5	7
	7	4.[illegible]	32.948	-	0.87574	7	5
	7B	4[illegible]	30.910	-	0.865[illegible]	6	6
	[illegible]	2.[illegible]	11.860	151	0.9810	3	2
	9	3.327	19.767	145	0.95119	4	4
7,6		1.780	19.767	15[illegible]	0.97336	1	1
	5	2.684	30.910	147	0.92603	2	4
	6	6.190	54.917	-	0.68454	5	7
	7	7.775	37.437	-	0.71929	7	6
	7B	6.956	37.437	-	0.71982	6	5
	8	3.[illegible]24	12.642	153	0.96720	3	2
	9	4.822	21.071	149	0.94013	4	3

A comparison of Table 4-14 with Table 4-8 shows the effect of this variation on the cost rankings. There are two rank changes for Payload 1,2 and none for the other payloads. The rankings of Test Plans 6 and 7B are affected. Except for Payload 1,6, Test Plan 4 ranks first, followed by Test Plans 5, 8, 9, 6, 7B, and 7, which has the highest optimum cost. For Payload 1,6 the rankings of Test Plans 6 and 7B are reversed.

The optimum expected costs are higher than the baseline costs in all cases. The amount of the increase varies with payload and test plan from \$0.088M for Payload 7,2 with Test Plan 4 to \$0.867M for Payload 1,6 with Test Plan 7. Except for Payload 1,6, the smallest increase is obtained for Test Plan 4, followed by Test Plans 5, 6, 8, 9, 7B and 7, which has the largest increase. For Payload 1,6 the amount of the increase for Test Plans 6 and 8 is reversed.

The optimum component vibration levels are the same or lower than the baseline vibration levels in all cases. The amount of the decrease varies with payload and test plan from 0 g rms to 9.575 g rms. No change in the vibration level occurs 5 times. The maximum change of 9.575 g rms occurs for Payload 1,2 with Test Plan 6.

The optimum assembly acoustic test levels are the same or lower than the baseline acoustic levels in all cases. The amount of the decrease varies with payload and test plan and is either 0 or 2 dB.

A comparison of Table 4-14 with Table 4-8 shows the effect of the degree of redundancy on the reliability rankings. There are two rank changes for Payloads 1,2, 1,6, and 7,6 and four rank changes for Payload 7,2. For Payload 1,2 the rankings of Test Plans 4 and 8 are affected; for Payloads 1,6 and 7,6, Test Plans 5 and 9; for Payload 7,2, Test Plans 5, 7, 7B, and 9. Except for Payloads 7,2 and 7,6, Test Plan 4 ranks first, followed by Test Plans 8, 5, 9, 7B, 7 and 6, which has the lowest vibroacoustic reliability. For Payload 7,2 the rankings of Test Plans 7 and 7B are reversed and for Payload 7,6 the rankings of Test Plans 5 and 9 are reversed.

4.3.4 COMPONENT RETEST/REPAIR COST

Only one variation of the component retest/repair cost was considered. This variation was a $15,000 component retest/repair cost when a failure occurs during component testing, a $30,000 component retest/repair cost when a failure occurs during assembly testing, and a $40,000 component retest/repair cost when a failure occurs during flight. The changes were considered as a group. The baseline considers a $15,000 cost when a failure occurs at any level. The sixth digit of the six-digit case code identifies the component retest/repair cost. The case code for the data of this variation is XY0001, where X is the test plan ID and Y is the payload ID defined in Section 3.1. The TECF and FFP data are given in the Addendum and the TECF data for the assembly test level at which the optimum cost occurs are shown in Figures 4-1 to 4-28. On the figures the symbol for this variation is ↑. A summary of the optimum data by payload is given in Table 4-15.

A comparison of Table 4-15 with Table 4-8 shows the effect of this variation on the cost rankings. There are no changes. Test Plan 4 ranks first for all payloads, followed by Test Plans 5, 8, and 9; Test Plan 7 ranks last. For Payloads 1,2 and 1,6 Test Plan 7B ranks fifth and Test Plan 6 ranks sixth. These rankings are reversed for Payloads 7,2 and 7,6.

Table 4-15

Summary of Optimums By Payload
Variation 0001
Phase C Component/Assembly/Flight Retest/Repair Cost = \$15K/\$30K/\$40K

Payload	Test Plan	Expected Cost (\$ x 10^6)	Component Vibration Test/Design Level (g rms)	Assembly Acoustic Test Level (dB)	Associated Vibroacoustic Reliability	Cost Rank	Reliability Rank
1,2	4	1.078	23.942	151	0.99814	1	1
	5	1.505	32.948	147	0.99646	2	3
	6	3.232	54.917	-	0.98018	6	7
	7	3.810	39.906	-	0.98436	7	6
	7B	3.015	39.906	-	0.98507	5	5
	8	1.806	16.321	151	0.99775	3	2
	9	2.325	22.461	147	0.99565	4	4
1,6	4	1.356	27.204	153	0.99677	1	1
	5	1.838	35.121	151	0.99562	2	3
	6	5.085	[illegible]8.539	-	0.94885	6	7
	7	5.268	48.333	-	0.96737	7	6
	7B	4.460	48.333	-	0.96306	5	5
	8	2.212	18.544	153	0.99622	3	2
	9	2.770	23.942	151	0.99490	4	4
7,2	4	1.326	22.461	151	0.98660	1	1
	5	1.727	30.910	147	0.97466	2	3
	6	3.584	51.520	-	0.87212	5	7
	7	4.417	35.121	-	0.88493	7	6
	7B	3.620	35.121	-	0.88557	6	5
	8	2.305	15.311	151	0.98384	3	2
	9	2.826	21.071	147	0.96877	4	4
7,6	4	1.870	25.521	151	0.96333	1	1
	5	2.503	30.910	149	0.95[illegible]09	2	3
	6	6.204	54.917	-	0.68366	5	7
	7	7.314	42.537	-	0.76080	7	6
	7B	6.501	42.537	-	0.76135	6	5
	8	3.491	17.397	151	0.95616	3	2
	9	4.276	21.071	149	0.94010	4	4

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The optimum expected costs are higher than the baseline costs in all cases. The amount of the increase varies with payload and test plan from $0.019M for Payload 1,6 with Test Plan 9 to $0.396M for Payload 7,6 with Test Plan 6. Except for Payload 1,6, the smallest increase is obtained for Test Plan 5, followed by Test Plans 9, 4, 8, 7, 7B and 6, which has the largest increase. For Payload 1,6 the amount of the increase for Test Plans 5 and 9 is reversed and for Test Plan 8 it is larger than that of Test Plans 7 and 7B.

The optimum component vibration levels are the same or higher than the baseline vibration levels in all cases. The amount of the increase varies with payload and test plan from 0 g rms to 6.178 g rms. No change in the vibration level occurs 13 times. The maximum change of 6.178 g rms occurs for Payload 7,2 with Test Plan 6.

The optimum assembly acoustic levels vary with payload and test plan. For Payload 1,2 with Test Plan 8 and Payload 7,6 with Test Plans 4 and 8 they are lower than the baseline acoustic levels. For Payloads 1,6 and 7,2 with Test Plan 5 they are higher than the baseline values. For all other cases they are the same as the baseline values.

A comparison of Table 4-15 with Table 4-8 shows the effect of the component retest/repair cost on the reliability rankings. There are two rank changes for Payloads 1,2, 1,6, and 7,2 and no rank changes for Payload 7,6. For Payload 1,2 the rankings of Test Plans 4 and 8 are affected; for Payloads 1,6 and 7,2, Test Plans 5 and 9. For all payloads Test Plan 4 ranks first, followed by Test Plans 8, 5, 9, 7, and 6, which has the lowest vibroacoustic reliability.

4.3.5 PARAMETER VARIATIONS CLOSURE

In the above discussions of the effects of the variations of key parameters it has been shown that the cost and vibroacoustic reliability rankings vary with the payload, test plan, and parameter variation. The cost rankings are summarized by payload in Table 4-16 and the vibroacoustic reliability rankings are summarized by payload in Table 4-17. In Table 4-16 only Test Plan 4 holds the same ranking for all cases. In Table 4-17 no test plan holds the same ranking for all cases. The sensitivity of the various parameters on the cost and reliability rankings is illustrated in Figure 4-29. This figure shows histograms of the rankings for each test plan. These histograms consider the rankings of the test plans for 28 cases, seven conditions (baseline and six variations) of the four payload configurations.

The cost histograms show that, for the majority of the 28 cases, Test Plan 4 ranked first, Test Plan 5 ranked second, Test Plan 8 ranked third, Test Plan 9 ranked fourth, Test Plan 7B ranked fifth, Test Plan 6 ranked sixth. and Test Plan 7 ranked seventh. The reliability histograms show that, for the majority of the 28 cases, Test Plan 4 ranked first, Test Plan 8 ranked second, Test Plan 5 ranked third, Test Plan 9 ranked fourth, Test Plan 7B ranked fifth, Test Plan 7 ranked sixth, and Test Plan 6 ranked seventh.

Table 4-16

Cost Rank Summary

Payload	Test Plan	Parameter Variation						
		0000	1000	2000	0100	0200	0010	0001
1,2	4	1	1	1	1	1	1	1
	5	2	2	3	2	2	2	2
	6	6	6	6	6	6	5	6
	7	7	7	7	7	7	7	7
	7B	5	4	5	5	5	6	5
	8	3	3	2	3	3	3	3
	9	4	5	4	4	4	4	4
1,6	4	1	1	1	1	1	1	1
	5	2	2	2	2	2	2	2
	6	6	5	7	7	7	6	6
	7	7	7	6	6	6	7	7
	7B	5	6	5	5	5	5	5
	8	3	3	3	3	3	3	3
	9	4	4	4	4	4	4	4
7,2	4	1	1	1	1	1	1	1
	5	2	2	2	2	2	2	2
	6	5	4	6	6	6	5	5
	7	7	7	7	7	7	7	7
	7B	6	5	5	5	5	6	6
	8	3	3	3	3	3	3	3
	9	4	6	4	4	4	4	4
7,6	4	1	1	1	1	1	1	1
	5	2	2	2	2	2	2	2
	6	5	3	7	6	6	5	5
	7	7	7	6	7	7	7	7
	7B	6	6	5	5	5	6	6
	8	3	4	3	3	3	3	3
	9	4	5	4	4	4	4	4

Table 4-17

Vibroacoustic Reliability Rank Summary

Payload	Test Plan	Parameter Variation						
		0000	1000	2000	0100	0200	0010	0001
1,2	4	2	1	1	1	1	1	1
	5	3	3	3	4	3	3	3
	6	7	5	7	7	7	7	7
	7	6	7	6	6	6	6	6
	7B	5	6	5	5	5	5	5
	8	1	2	2	2	2	2	2
	9	4	4	4	3	4	4	4
1,6	4	1	1	2	1	1	1	1
	5	4	3	3	3	3	3	3
	6	7	5	7	7	7	7	7
	7	6	7	6	6	6	6	6
	7B	5	6	5	5	5	5	5
	8	2	2	1	2	2	2	2
	9	3	4	4	4	4	4	4
7,2	4	1	1	1	1	1	1	1
	5	4	3	3	3	3	3	3
	6	7	5	7	7	7	7	7
	7	6	7	6	6	6	5	6
	7B	5	6	5	5	5	6	5
	8	2	2	2	2	2	2	2
	9	3	4	4	4	4	4	4
7,6	4	1	1	1	1	1	1	1
	5	3	3	3	3	4	4	3
	6	7	5	7	7	7	7	7
	7	6	7	6	6	6	6	6
	7B	5	6	5	5	5	5	5
	8	2	2	2	2	2	2	2
	9	4	4	4	4	3	3	4

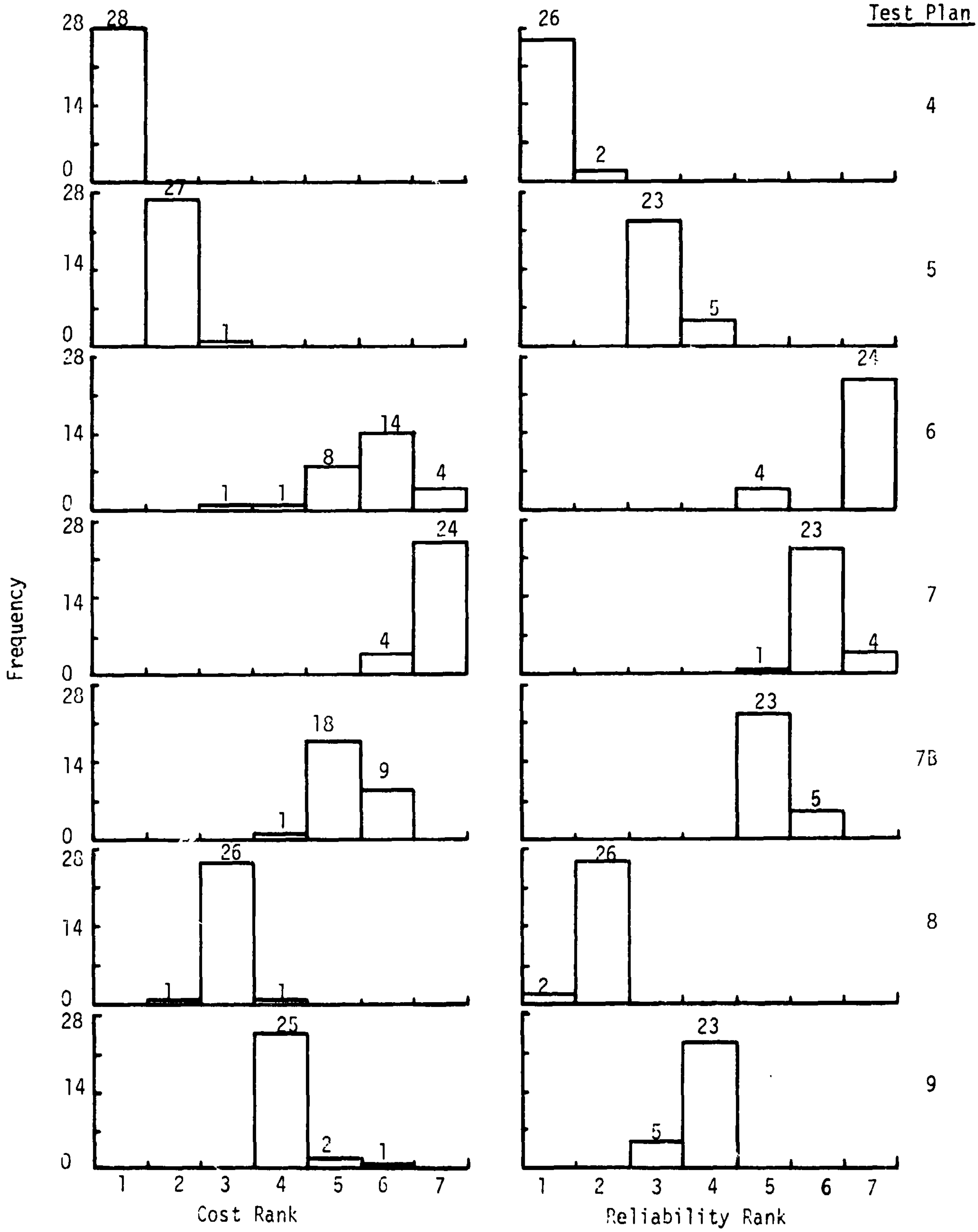

Figure 4-29 Cost Rank and Vibroacoustic Reliability Rank Histograms

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

On the basis of this Phase C study the following conclusions, regarding alternate vibroacoustic test plans for the four facility type Shuttle Spacelab payload configurations considered, are made for the revised baseline and parameter variations:

1. Statistical decision models provide a viable method of evaluating the cost effectiveness and the associated test levels of alternate vibroacoustic test plans. The methodology modified herein provides a major step toward the development of a realistic tool to quantitatively tailor vibroacoustic test programs to specific payloads. Component redundancy and partial loss of flight data are considered. Most direct and probabilistic costs and incipient failures resulting from vibroacoustic ground tests are treated. The results obtained from the application of the models to facility type Shuttle Spacelab payload configurations are rational and identify new low cost test plans. Optimum costs and the associated component vibration and assembly acoustic test levels are obtained for each alternate vibroacoustic test plan. To interpret the results relative to a particular test plan and payload, the modeling simplifications must be considered.

2. On the basis of minimizing the expected project cost, the vibroacoustic test plans evaluated for the baseline parameters had the following rank:

   (1) Test Plan 4 using subassembly testing only

   (2) Test Plan 5 using system testing only

   (3) Test Plan 8 using component and subassembly testing

   (4) Test Plan 9 using component and system testing

   (5) Test Plan 7B using component and protoflight structure testing or

   Test Plan 6 using no testing

   (7) Test Plan 7 using component testing only

   The fifth ranking depended on whether the payload configuration had a single experiment or multiple experiments.

3. On the basis of the vibroacoustic reliability associated with the minimum expected project cost, the test plans evaluated for the baseline parameters had the following rank:

    (1) Test Plan 4 or

    Test Plan 8

    (3) Test Plan 5 or

    Test Plan 9

    (5) Test Plan 7B

    (6) Test Plan 7

    (7) Test Plan 6

    The first and third rankings varied with the payload configuration.

4. For the test plans evaluated with the baseline parameters the highest vibroacoustic test levels occurred for the payload configuration having a single complex experiment while the lowest test levels occurred for the payload configuration having multiple less complex experiments. The vibroacoustic reliability associated with the optimum cost was lower for the multiple experiment payload configurations.

5. For the vibroacoustic test plans evaluated with the parameter variations the lowest expected project costs and the associated test levels were obtained for the 135 dB shuttle payload bay internal acoustic environment.

6. The most sensitive parameters of those varied in this study were the shuttle payload bay internal acoustic environment and the STS launch cost.

7. For the 28 parameter variation cases considered for each test plan Test Plan 4 ranked first most frequently in the cost ranking, followed by Test Plans 5, 8, 9, 7B, 6, and 7. Test Plan 4 also ranked first most frequently in the reliability ranking, followed by Test Plans 8, 5, 9, 7B, 7, and 6.

8. For the test plans evaluated with the shuttle payload bay internal acoustic environment varied the expected project cost and the associated vibroacoustic test levels increased when the environment level increased.

9. For the test plans evaluated with the STS launch cost varied the expected project cost and the associated vibroacoustic test levels increased when the launch cost increased.

10. For the test plans evaluated with the degree of redundancy in the housekeeping components varied the expected project cost increased but the associated vibroacoustic test levels decreased when the degree of redundancy increased.

There were five cases in which the component vibration level did not change but there were only four cases in which the assembly acoustic level changed. Because of the lower test levels the associated vibroacoustic reliability decreased in all but four cases.

11. For the test plans evaluated with the component retest/repair cost varied the expected project cost and the associated component vibration level increased when the component retest/repair cost increased. There were five cases in which the assembly acoustic level changed; three cases were lower and two were higher.

12. The proof test of a flight structure designed with a moderate increase in safety factor was the most cost effective of the structural options considered. The cost of performing component and protoflight structure testing was approximately $0.8 million less than the cost of performing component only testing.

13. Relatively high acoustic test levels should be used for assembly level testing. For Test Plan 4, which utilizes subassembly testing only and was the most cost effective test plan considered, the assembly test level associated with the optimum expected project cost was either 151 dB or 153 dB for the baseline variation. The assembly level test provides an effective method of locating marginal component designs because of the improved simulation of the flight environment, resulting in a reduced variation in the component environment. On the other hand, component testing is not as effective since high vibration levels are required to achieve payload reliability, resulting in a significant increase in component development costs.

14. The modification of the models to provide flight by flight failure probabilities gave a more accurate representation of the cumulative multiple mission damage. Although this study was restricted to ~ 15 mission payload, this also gives us the mechanism to study the effects of the number of missions on the evaluation of the vibroacoustic test plans.

15. The inclusion of the cost of designing components to withstand higher vibration levels provided optimum expected project costs and the associated test levels for each test plan considered.

16. For comparable test sequences the expected project costs obtained for this Phase C study were less than those obtained for the Phase B study, primarily because of the deletion of all test dedicated hardware.

5.2 RECOMMENDATIONS

The following specific recommendations are made:

1. As a result of the evaluation of the alternate vibroacoustic test plans for the revised baseline and parameter variations, the effects of other key parameters should be examined. These parameters include the following:

   (1) Fundamental to the developed methodology is the untested component strength distribution. The results of component testing on various spacecraft programs encompassing in excess of 300 components are used to determine the proportion of components which pass the component vibration tests as a function of the test level. A semilog graph of the data is a straight line. The effects of this parameter on the vibroacoustic test plan evaluation should be examined by varying the slope of this line.

   (2) In the studies performed to date the number of components in the housekeeping section of the payload reliability model has been fixed at 16 plus the structure. All payload configuration variations have been made by varying the number of experiments and the number of components in each experiment. It has been shown that the results are payload configuration dependent. The effects of variations in the number of housekeeping components should be investigated.

   (3) All data has been obtained for a 15 mission facility type payload. The payloads that will be carried on the shuttle have a wide variety of characteristics. One of these characteristics is the number of missions that the payload is planned to fly. Since the modified models can evaluate flight by flight failure probabilities, the effects of variations in this key parameter should be determined as soon as possible.

   (4) Costs of component, subassembly, system, and structure tests.

4. It was demonstrated in the Phase C study that the expected project cost increases as the degree of redundancy is increased. A study should be initiated to determine whether the components that perform certain functions could be moved from the housekeeping section, where redundancy is required, to the experiment section, where no redundancy is required. One consequence of this move would be the requirement for more components, even though they are redundant, particularly for payloads with a reasonable number of experiments. A tradeoff between the cost of a larger number of nonredundant components and the cost of components with higher degrees of redundancy should be established.

5. The current reliability model requires that each experiment has the same number of components. To provide greater flexibility in studying a variety of payloads, ways to modify this requirement should be investigated.

6. The decision models should be applied to a variety of planned Shuttle Spacelab payloads to determine the optimum vibroacoustic test plan and guide their development. Major emphasis should be placed on minimizing cost. By quantitatively evaluating the cost effectiveness of alternate vibroacoustic test plans early in the conceptual design phase, requirements can be established for specific payloads which result in reduced development costs. This has been initiated by applying the modified decision models to evaluate the seven vibroacoustic test plans of Phase C for a representative EVAL (Earth Viewing Applications Laboratory) payload, Reference 3.

7. The evaluation of the alternate vibroacoustic test plans for free flying shuttle payloads and payloads using expendible launch vehicles should be investigated. Because major changes to current practices are planned for Shuttle Spacelab payloads, this type of payload should be examined soon. However, the methodology is also applicable to current payloads and shuttle launched free flying payloads. Potential cost savings for these payloads should be examined.

8. The feasibility of extending the methodology to include thermal-vacuum and other test environments should be considered.

9. In the process of developing the methodology to evaluate alternate vibroacoustic test plans during the Phase B and Phase C studies considerable computer coding has been written to generate the data obtained. In most cases these codes were written to obtain data for a specific test plan. To become useful for evaluating a variety of specific payload configurations, these programs should be placed on production status. To achieve this status the computer codes for the test plans of both Phase B and Phase C should be reviewed, coordinated, optimized, and documented. Wider usage should be obtained by making the code compatible with the NASA-GSFC computer. The capability to plot selected data on the CALCOMP, or other, plotter should enhance the application of this methodology.

REFERENCES

1. "Space Shuttle System Payload Accommodations, Level II Program Definition and Requirements", JSC 07700, Volume XIV, Lyndon B. Johnson Space Flight Center.

2. Wahle, C.V. and Gongloff, H.R., "Vibroacoustic Test Plan Evaluation", GE Document No. 76SDS4223, June 1976.

3. "EVAL System Concept Definition, Partial Spacelab Payload Technical Report", GE Document No. 76SDS4269, September 1976.

6-DIGIT CASE CODE

1st DIGIT - TEST PLAN ID

1 = TP-4, Test Plan 4
2 = TP-5, Test Plan 5
3 = TP-6, Test Plan 6
4 = TP-7, Test Plan 7
5 = TP-7B, Test Plan 7B
6 = TP-8, Test Plan 8
7 = TP-9, Test Plan 9

2nd DIGIT - PAYLOAD ID

1 = 1,2, Payload 1,2
2 = 1,6, Payload 1,6
3 = 7,2, Payload 7,2
4 = 7,6, Payload 7,6

3rd DIGIT - SHUTTLE PAYLOAD BAY INTERNAL ACOUSTIC ENVIRONMENT ID

0 = Baseline = 145 dB OA
1 = 1st Variation = 135 dB OA
2 = 2nd Variation = 150 dB OA

4th DIGIT - STS LAUNCH COST ID

0 = Baseline = $13,500,000
1 = 1st Variation = $17,500,000
2 = 2nd Variation = $21,500,000

5th DIGIT - DEGREE OF REDUNDANCY IN HOUSEKEEPING SECTION ID

0 = Baseline = Single
1 = 1st Variation = Double

6th DIGIT - COMPONENT/ASSEMBLY/FLIGHT RETEST/REPAIR COST ID

0 = Baseline = $15,000/$15.000/$15,000
1 = 1st Variation = $15,000/$30,000/$40,000

NOTE: 4-DIGIT CASE CODE IS LAST FOUR DIGITS OF 6-DIGIT CASE CODE